NUMO
原子力発電環境整備機構

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The NUMO Pre-siting SDM-based Safety Case

November 2021

Nuclear Waste Management Organization of Japan (NUMO)

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1 INTRODUCTION

This report is a translation of the original Japanese Safety Case (SC) Report, however it is important to note that it does not represent an exact 1:1 translation. The content has been slightly modified in places to make it more easily understandable to an international audience, who may not be fully familiar with the Japanese radioactive waste management programme.

1.1 Basic concept of geological disposal

The use of nuclear power generates a range of radioactive wastes. It is the ethical responsibility of the current generation to identify specific measures for the safe disposal of such waste and to ensure steady progress towards implementation of disposal projects.

In Japan, where energy resources are scarce, the basic policy involves a nuclear fuel cycle in which uranium and plutonium from spent fuel are reused after reprocessing. Reprocessing results in highly radioactive liquid waste, which is vitrified to produce a stable, solid, borosilicate glass high-level radioactive waste (HLW) that is suitable for disposal. In some other countries with nuclear programmes, direct disposal of spent fuel is also adopted as a method of waste management. Although the radioactivity of HLW decays over time, it remains significant over an extremely long time, as shown in Figure 1.1-1. However, after a few tens of thousands of years, this becomes equivalent to the radioactivity of the uranium ore from which it was produced.

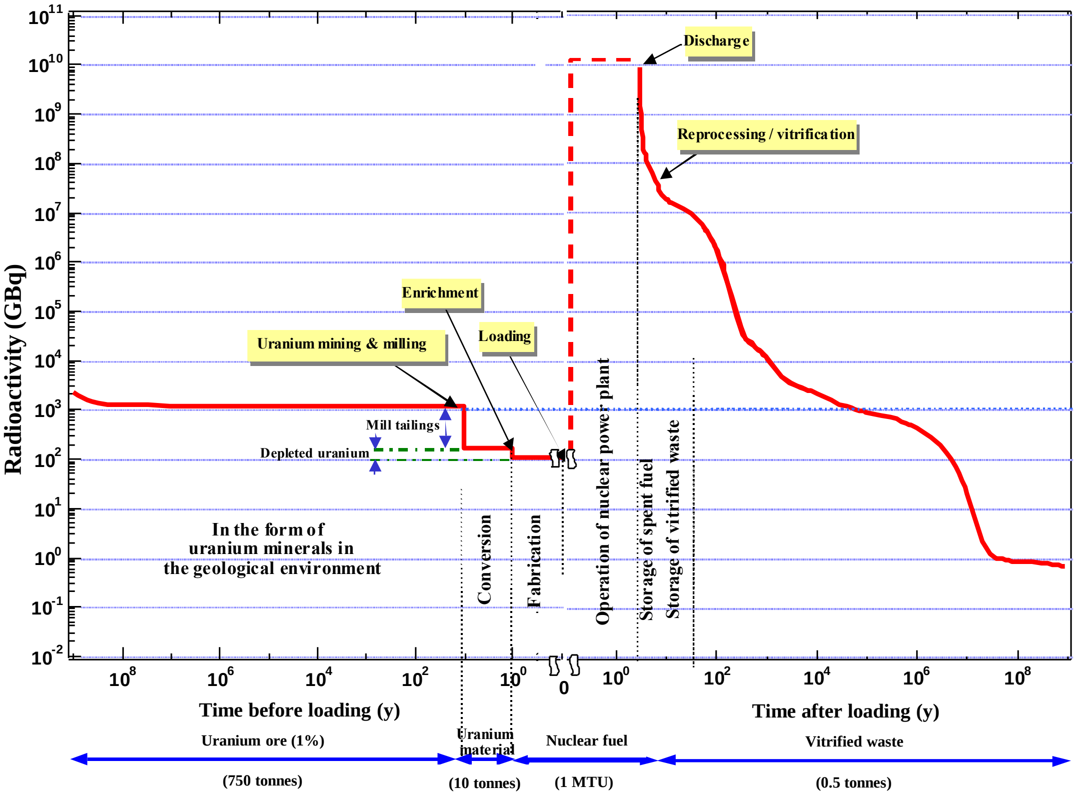

Figure 1.1-1 Temporal change of radioactivity for vitrified HLW (modified from JNC, 2000 [1], 1 MTU = 1 metric tonne uranium). Note that the weight of the vitrified waste generated by JFNL is 400 kg (see Section 2.1.1) and its canister loading is 0.8. 1 MTU corresponds to 500 kg of glass for fuel reprocessed by JNFL

As a result of numerous studies on methods for disposing of long-lived radioactive wastes, mainly by countries using nuclear power, it is internationally recognised that geological disposal is the most promising strategy that has no significant impact on the living environment and requires no direct human control (OECD/NEA 1995 [2]).

Repositories for the disposal of higher-level radioactive wastes generally adopt a system of multiple engineered barriers (engineered barrier system - EBS), within a suitable deep geological setting. Together, the EBS and the natural geological barriers ensure isolation of the waste from the biosphere for a significant period of time (1 to 10 ky or more) after repository closure. During this period, most radionuclides (RNs) will have decayed completely or to a level where any radiological risk is acceptably low. In addition, the environment deep underground is less susceptible to human activities and various natural perturbing phenomena affecting the surface, such as floods and landslides.

1.2 Background to deep geological disposal in Japan

In Japan, the Japan Atomic Energy Commission (JAEC) promulgated the “Basic concepts for high-level radioactive waste disposal” in 1998 [3]. Further to this, “H12: Project to establish the scientific and technical basis for HLW disposal in Japan”, (hereafter the “H12 Report”), produced by the Japan Nuclear Cycle Development Institute (JNC; now Japan Atomic Energy Agency - JAEA) in 2000 (English edition) [1], compiled the results of research and development (R&D) conducted since 1976 and established the fundamental feasibility of geological disposal.

Based on these reports, the “Act on Final Disposal of Specified Radioactive Waste” (hereafter the “Final Disposal Act”) was enacted in 2000. “Specified Radioactive Waste[1]” initially referred to vitrified high-level radioactive waste resulting from the reprocessing of spent fuel, but was extended to include what is termed TRU waste, produced from both reprocessing and MOX (mixed U/Pu oxide) fuel fabrication. Although some TRU waste contains significant quantities of transuranic RNs, it also contains a wide range of other RNs and the term TRU waste as used in this report refers specifically to the fraction of such material intended for geological disposal, unless otherwise specified. “The second progress report on research and development for TRU waste disposal in Japan” [4] (hereafter the “TRU-2 Report”), compiled by JAEA and the Federation of Electric Companies of Japan (FEPC) in 2007, formed the basis for this revision of the Final Disposal Act.

Based on the Final Disposal Act, the Nuclear Waste Management Organization of Japan (NUMO) was established in 2000 as the organisation responsible for project implementation. The site selection process specified in the Act consists of three phases of investigation: literature surveys (LS), preliminary investigations (PI) and finally, detailed investigations (DI). In 2002, NUMO issued a nationwide call for volunteer municipalities to initiate the repository siting process.

Since its establishment, NUMO has been conducting R&D to enhance the reliability of the technical basis presented in the H12 report, with the focus on safety and feasibility. In addition, JAEA has also been carrying out research in order to advance the Japanese geological disposal programme – in particular in two underground research laboratories

[1] The term “specified” radioactive waste was changed in 2015 when the Basic Policy on Final Disposal of Higher-level Radioactive Wastes was revised (see Section 1.3). The term now used is “designated” radioactive waste. N.B. This footnote is not included in the Japanese version of the report.

(URLs), Mizunami (in crystalline rock) and Horonobe (in sedimentary rock) - to further improve geological disposal technology and develop safety assessment methodology.

Results of the research performed by NUMO were compiled and published in a series of technical documents (in Japanese) leading up to publication of the report “Safety of the geological disposal project 2010” [5] (hereafter the “2010 Report”), which summarises NUMO’s progress in establishing technologies for safe geological disposal. NUMO has been continuously developing the technologies required for safe implementation of the disposal project and, in coordination with National Government, the electricity utilities and other relevant organisations, has made significant efforts in communication, in order to build public acceptance for geological disposal (e.g., public hearings and public information activities). Early efforts resulted in Toyo town in Kochi prefecture coming forward to make an application for a literature survey in January 2007. However, soon after the results of a mayoral election held in April 2007, the application was withdrawn and no literature survey was initiated.

The accident at the Tokyo Electric Power Co., Ltd. (TEPCO) Fukushima Daiichi Nuclear Power Plant occurred as a result of the Great Tohoku Earthquake in March 2011, causing loss of public trust in both the nuclear industry and associated organisations. For the geological disposal project, the Science Council of Japan recommended in 2012 that the policy on disposal of HLW should be fundamentally reviewed. The Science Council also suggested that extended storage of waste should be introduced in order to allow more time for both progress in research to enhance the safety of geological disposal and building of social consensus. In particular, based on the lack of consensus among geoscience experts regarding the concept of long-term safety and the presence of suitable geological environments in Japan, the Science Council insisted that the limitations of scientific knowledge and associated technology should be recognised and a forum for specialist deliberations be established [6]. In response to this, the Japan Atomic Energy Commission (JAEC) proposed research on the feasibility of geological disposal that reflected the latest findings in the field of geosciences and sharing of results with the public [7].

1.3 Revised strategy for geological disposal

Based on the situation described in the previous section, two expert working groups were set up in 2013 by the National Advisory Committee for Natural Resources and Energy; one covering radioactive waste and the other geological disposal technology.

The Radioactive Wastes Working Group (hereafter the Radioactive Wastes WG) discussed re-establishing policies on geological disposal with the aim of highlighting areas to be addressed in advancing the project [8]. Key conclusions include:

- It is internationally recognised that geological disposal remains the most appropriate final disposal method for higher activity radioactive waste. Even in Japan, despite the challenging boundary conditions, geological disposal is based on an extensive scientific knowledge base and its feasibility has been demonstrated. Geological disposal is the sole implementation method defined in law.
- A mechanism for reversibility (capability to reverse or change decisions later) and retrievability (capability to recover the emplaced waste from the repository) should be ensured to allow reconsideration of the decision on final disposal by current and future generations, considering both existing uncertainties and enhanced social consensus on geological disposal.

- To improve the site selection process, the Government should provide an explanation of the required geological environment characteristics from a scientific point of view and promote understanding of site selection, showing areas that are considered to be more suitable from a scientific viewpoint.
- It will be important for the implementing organisation and the scientific community to establish the technical reliability of geological disposal by continuously reviewing and utilising the latest scientific knowledge, establishing R&D on alternative disposal options in parallel with site selection and promoting stepwise social consensus-building regarding the acceptability of geological disposal.

Characteristics of the geological environment in Japan and its long-term stability were discussed by the Geological Disposal Technology WG [9], based on the latest knowledge obtained since the H12 report. Key conclusions include:

- From the viewpoints of thermal, rock-mechanical, hydrogeological and geochemical characteristics, potentially favourable geological environments that provide the necessary conditions for hosting a geological disposal system have been identified and are widely distributed throughout Japan.
- Through appropriate stepwise site investigations, sites with a favourable geological environment and assured long-term stability can be selected, despite the effects of long-term evolution in all such settings.

Taking such input into account, the Government revised the “Basic Policy on Final Disposal of Designated Radioactive Wastes” (hereafter the “Basic Policy on Final Disposal”) in May 2015, and the following points were clearly stated:

- Clarification of the current generation's responsibilities and assuring flexibility for future generations for decision-making (e.g., technological developments, including alternative options, and making progress in geological disposal are the responsibility of this generation (i.e., burdens should not be passed on to the next generation), while ensuring reversibility and retrieval options for future generations)[2].
- The need to foster both nationwide and regional understanding of the issues involved (e.g., by establishing regular, open dialogue).
- The National Government is to take the lead in key areas, such as presenting regions that are considered to be scientifically more suitable, making proposals to relevant local governments to support their understanding and cooperation in research, etc.
- Supporting relevant regions (e.g., establishing dialogue for building consensus).
- Improving the implementation system (e.g., strengthening NUMO’s management system, increasing the involvement of JAEC in order to carry out continuous evaluations of progress in technological development and thus ensure reliability, and to support the Nuclear Regulation Authority (NRA) in gradually developing appropriate safety guidelines).

It has thus been confirmed by the Government that geological disposal is the most technologically promising approach to managing the designated wastes and, in the light of the latest scientific findings, there is a good prospect of finding an environment suitable for

[2] Technology development is to include alternative options, as indicated in the Basic Policy on Final Disposal, which involves, e.g., research on the feasibility of direct disposal of spent fuel [10] and on the partitioning and transmutation of longer-lived radionuclides [11], implemented by JAEA and other organisations. NUMO focuses on geological disposal of designated wastes as defined in the Final Disposal Act and hence carries out no R&D on such alternative options.

geological disposal in Japan. Advancing this to implementing such disposal is the responsibility of the current generation.

In response to the revision of the Basic Policy on Final Disposal, the Radioactive Wastes WG decided to summarise the scientific characteristics of regions in the whole of Japan and discussed how to best establish dialogue and promote consensus building on this basis. The purpose is both to contribute to the selection of suitable sites and to provide an opportunity and materials for the general public to recognise and understand the need for final disposal and the significance of the project [12]. In addition, the Geological Disposal Technology WG discussed the requirements and criteria for scientific features of suitable regions from geoscientific and technical viewpoints.

As a result of these discussions, the Geological Disposal Technology WG published a report on the scientific features relevant for geological disposal [12]. In this report, as shown in Figure 1.3-1, the requirements and criteria for assessing site characteristics based on current knowledge prior to initiation of site investigation are described.

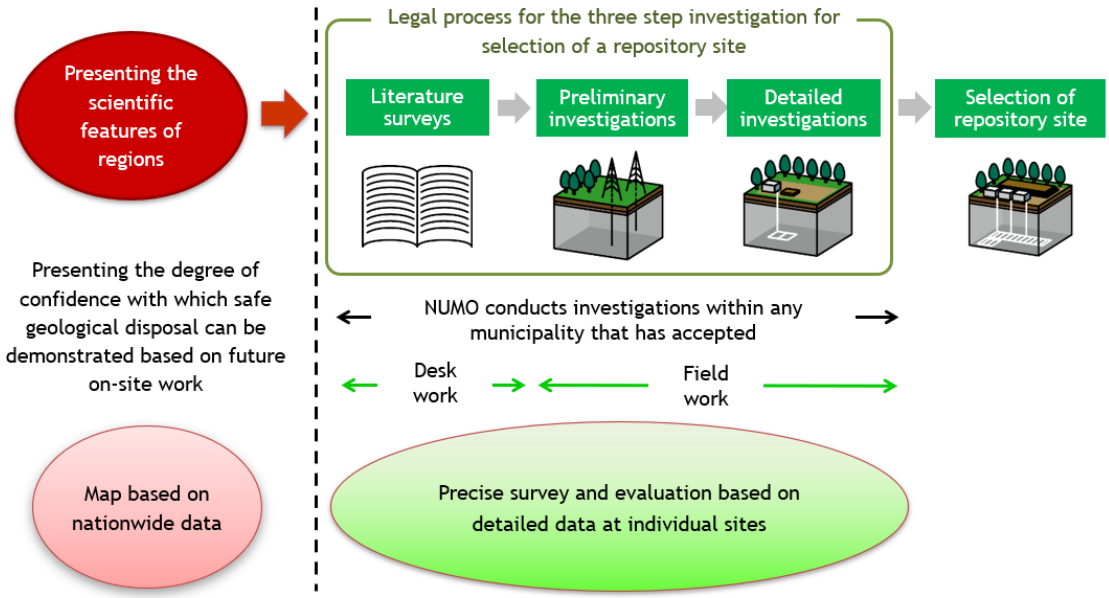

Figure 1.3-1 Relationship between sharing the scientific features of regions with municipalities and the site selection process, as defined in the Final Disposal Act [from 12]

This report considers the degree of confidence that safe geological disposal can be demonstrated based on future on-site work. Considering long-term stability, safety during construction and operation, safety during transport, and implementation practicality, requirements and criteria for identifying "preferred" and "non-preferred" sites are developed. For areas where there is a high probability that desirable characteristics can be confirmed, an additional positive criterion is that the distance from the coast is sufficiently short, recognising the advantages (e.g. relating to logistics and nuclear security) of waste transport from a coastal port to the repository site [12].

These requirements and criteria [12] led to publication in July 2017 of the 'nationwide map of "scientific features" relevant for geological disposal' [13] (Figure 1.3-2), hereafter the "Nationwide Map". This classified the whole of Japan into the following four regions:

- Those probably unsuitable from the viewpoint of long-term stability, such as those near volcanoes or active faults,

- Those with mineral resources such as oil fields and gas fields, which are undesirable from the viewpoint of future potential human intrusion,
- Those with a relatively high probability of being suitable due to lack of the above-mentioned undesirable requirements and criteria,
- Of the likely suitable areas, those preferable also in terms of transport advantages.

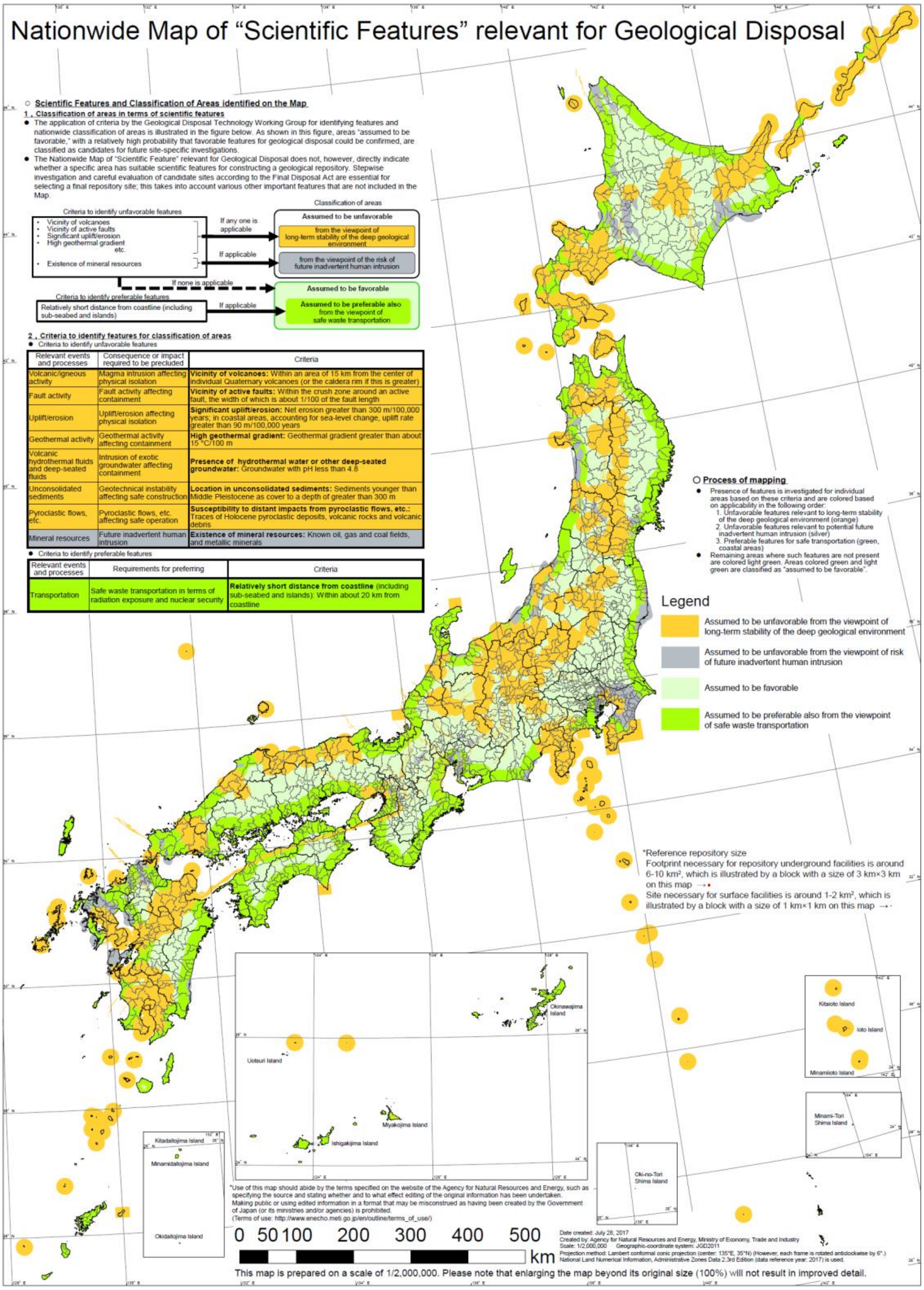

Figure 1.3-2 Nationwide map of “scientific features” relevant for geological disposal (Source: Ministry of Economy, Trade and Industry, 2017 [13])

In October 2020, the town of Suttu in Hokkaido prefecture applied for a literature survey to be undertaken. Additionally, another village in Hokkaido prefecture, Kamoenai, accepted a proposal for a literature survey by the Japanese Government. NUMO initiated literature surveys for both municipalities in November 2020. Currently, the Japanese Government and NUMO are continuing to promote dialogue throughout Japan to deepen public understanding of geological disposal based on the Nationwide Map. This may lead to further municipalities accepting to undertake a literature survey.

1.4 Overview of this report

1.4.1 Purpose of the report

When explaining site[3] selection activities based on the revised Basic Policy on Final Disposal, it is important for NUMO to be an organisation that is trusted by society and, in particular, by local communities that may accept a literature survey. Emphasis is thus on establishing dialogue that will convey how NUMO will assure safe geological disposal in a manner that will gain public confidence.

In addition, regarding the technical reliability of geological disposal, continuous evaluation based on the latest knowledge is required, as described in the Basic Policy on Final Disposal. Describing the methods for assuring safe disposal for relevant geological environments is thus an important requirement for NUMO.

Therefore, based on the latest scientific findings and technological developments, the study reported here was conducted for sites typical of those with a relatively high probability of being suitable, as indicated in the Nationwide Map. In accordance with the IAEA glossary, a safety case at this early stage of development should acknowledge the existence of any unresolved issues and should provide guidance for work to solve these issues during future stages of development. More specifically, this report has the purpose of:

- Illustrating the technology for surveying and evaluating sites with conditions necessary for isolating and containing designated radioactive wastes and ensuring no significant impacts on the human living environment for a variety of relevant geological environments in Japan.
- Presenting site descriptive models (SDMs) that capture key characteristics of information obtained from studies of deep geological environments in Japan, illustrating repository designs and engineering safety measures tailored to these which fulfil required safety functions.
- Demonstrating the safety of a potential repository site, both pre- and post-closure of the repository.
- Based on integration of the above input, identifying technical issues for further improvement and the required R&D needed for geological characterisation, repository design and safety assessment.

Based on this work, a methodology is outlined which focuses on assuring the safety of the implemented repository and involves stepwise tailoring to site-specific conditions. This methodology will be refined as the staged siting process progresses and updated to reflect future advances in science and technology.

[3] NUMO uses “site” as a term broadly referring to the area to be surveyed and, thereafter, the area finally selected as the location of the repository.

1.4.2 Production of the report

(1) Compilation as a safety case

In order to continually increase the confidence in the safety of geological disposal throughout the project period, at programme milestones we will summarise the evolving "safety case", which reflects the boundary conditions and incorporates the knowledge base at that time. The safety case[4] is a concept that involves structured demonstration of important repository safety aspects, providing this information in a manner accessible to key stakeholders [14]. This safety case has been prepared by NUMO as the project implementer. Its conclusions will be judged by Japanese stakeholders (regulatory bodies, National Government, local residents, general public, etc.), complemented by an international technical review, in terms of the credibility of the repository safety case presented.

This approach is consistent with the stated objectives of gaining the public confidence needed to advance the project to the next phase of siting by showing both the feasibility of safe geological disposal and NUMO's technical preparations for implementation. NUMO plans [5] to develop the safety case further, based on the characteristics of specific sites after the preliminary investigation phase. It will be updated again at later project milestones: site selection, disposal facility construction and subsequent licence applications. Thus, this report forms a basic safety case before any site has been identified, presenting the framework and information base for further safety cases to be produced in the future. NUMO has thus named this report "the NUMO Pre-siting SDM-based Safety Case" (hereafter the "NUMO SC"). The approach to safety case development has been described by several international organisations [14] [15] [16], resulting in the general structure shown in Figure 1.4-1 [16].

After establishing the "purpose and context" for a specific phase of the project, a "safety strategy" presents the approach to achieving the required safety level in terms of management of the whole project, site selection, repository design and safety assessment. Next, the "assessment bases" are documented, which include the disposal system concept (site characteristics and associated repository design), the scientific knowledge and methodology that form the basis for this, and the models, codes and databases supporting design and safety assessment. Safety will be demonstrated in a logical manner by way of a "safety assessment", together with "supporting evidence", such as that provided by natural analogues, that will reinforce/support the assessment results. Synthesis of both the safety assessment and the supporting arguments will demonstrate that NUMO can build/develop a safety case that is fit for purpose given specified boundary conditions.

This report is generally consistent with the role and basic structure of safety cases presented by a number of international organisations [14] [15] [16], considering not only the period post-closure of the repository but also that pre-closure, to ensure consistent treatment of safety as a whole.

[4] The IAEA (2012) [14] defines the safety case as follows: "The safety case is the collection of scientific, technical, administrative and managerial arguments and evidence in support of the safety of a disposal facility, covering the suitability of the site and the design, construction and operation of the facility, the assessment of radiation risks and assurance of the adequacy and quality of all of the safety related work associated with the disposal facility."

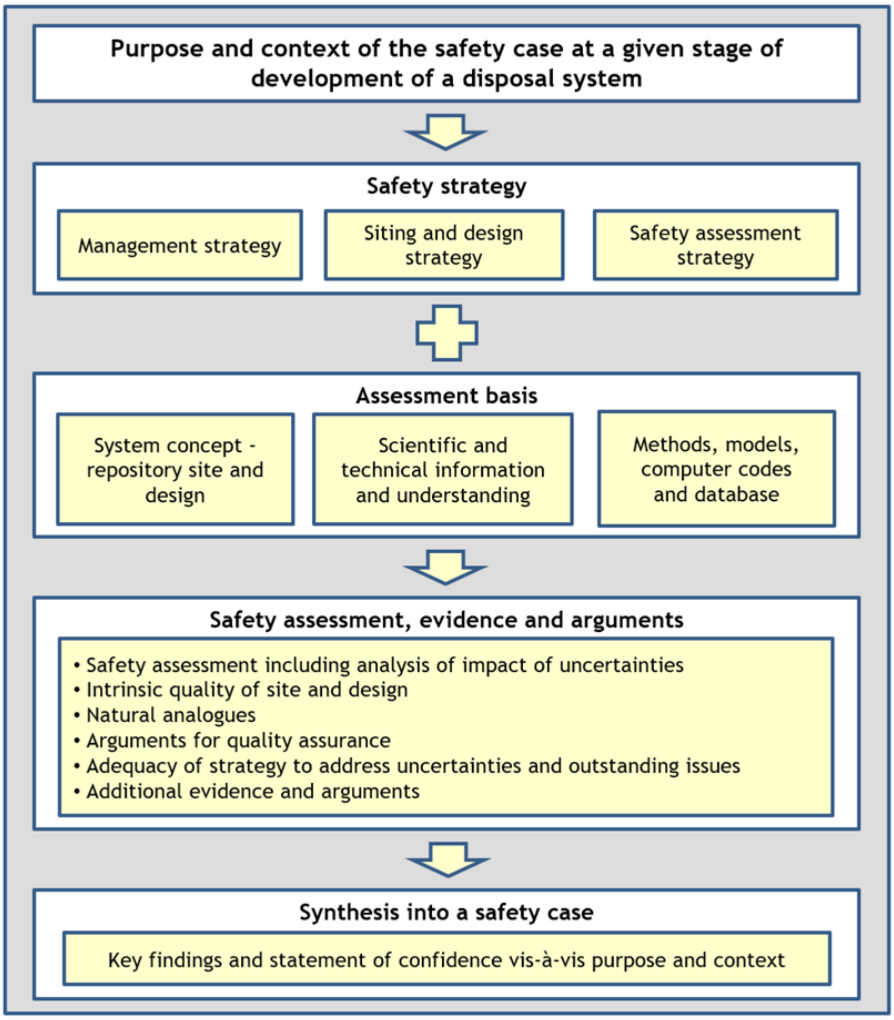

Figure 1.4-1 Structure of a safety case as shown by OECD/NEA [from 16]

(2) Structure of the report

For Japanese boundary conditions, the NUMO SC is modified from the basic structure shown in Figure 1.4-1, resulting in Figure 1.4-2, which also shows the relationship between each component of the safety case and the section of this report in which it is covered, as discussed further below.

Chapter 2 describes specific strategies and concepts devised by NUMO to facilitate progress towards safe implementation of a deep geological repository, managing site selection, repository design and safety assessment. Regarding the assessment basis, in response to the strategies shown in Chapter 2, methodologies and techniques for analysis along with associated models and data are used to illustrate the selection of appropriate sites, repository design and evaluation of pre-/post-closure safety.

Chapter 3 describes the geological investigation techniques used for characterisation of relevant sites and development of the site descriptive models (SDMs) that incorporate resulting site understanding. From these SDMs, tailored designs for the disposal system and associated safety assessment can be developed.

Chapter 4 describes repository design and engineering (including waste packages), based on a design philosophy and associated methodology to ensure that the required safety functions are both provided and are effective. This is illustrated by tailoring designs to the SDMs for the representative host rock types outlined in Chapter 3. The assumed construction, operation and closure procedures are illustrated and the engineering feasibility based on current technology assessed.

Chapter 5 evaluates operational safety, based on the repository designs presented in Chapter 4, and the procedures for repository construction, operation and closure.

Chapter 6 presents the required methodology and uses it to assess safety after repository closure for the concepts outlined in Chapter 4 in geological settings defined by the SDMs from Chapter 3.

Chapter 7 summarises input from previous chapters and describes its integration into a safety case. Based on this, it highlights topics for future R&D, with special emphasis on overarching issues not captured in the specialist chapters, and outlines how the safety case will develop further as siting progresses.

Chapter 8 concludes by summarising the key messages and perspectives in the report.

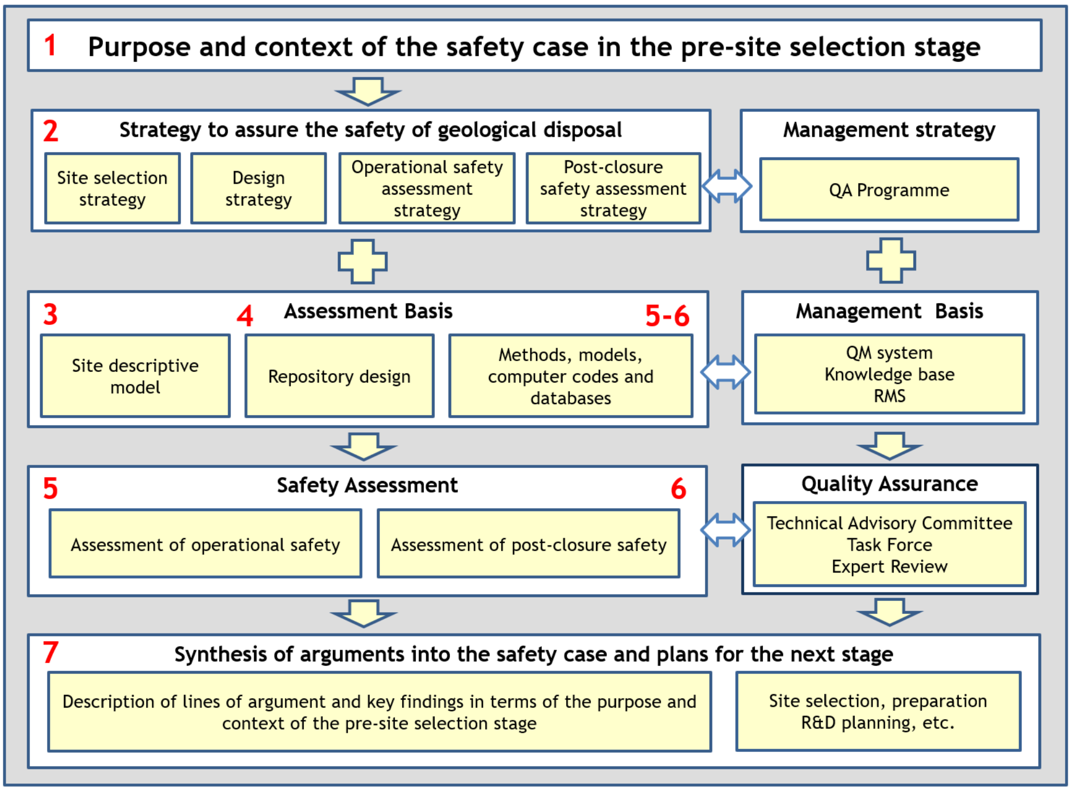

Figure 1.4-2 Adaptation of the NEA safety case outline to fit NUMO programme boundary conditions (with indication of the chapters of this report in which issues are addressed). QA: quality assurance, QM: quality management, RMS: requirements management system

(3) Report documentation

The safety case documentation is prepared at several hierarchical levels, as shown in Figure 1.4-3, so that the information can be accessed by readers depending on their needs and the level of technical detail they require.

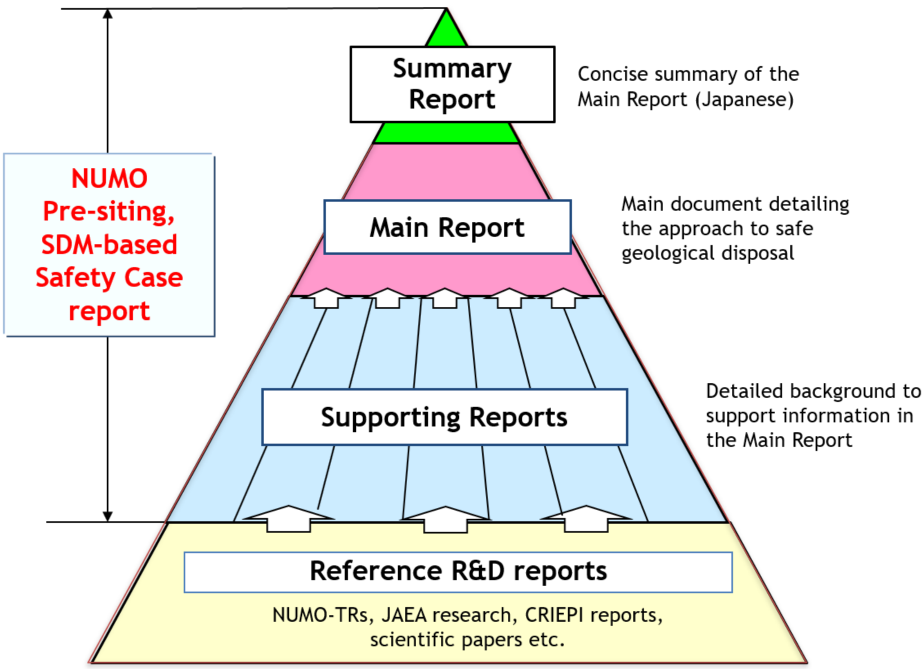

Figure 1.4-3 Overall structure of the safety case documentation

The safety case arguments are supported in more technical detail, progressing from the upper level to the lower level, while links and cross-references ensure traceability. The present report corresponds to the “Main Report”, forming the central part of the safety case, but is also linked to detailed information contained in the “Supporting Reports”.

A “Summary Report” has also been produced (in Japanese) in order to allow less technical readers to quickly and easily grasp the main points of the safety case. Many individual technical reports and scientific papers are referred to in this report, forming the technical fundamentals of the safety case. The Main Report and Supporting Reports together, are collectively called “the NUMO Pre-siting SDM-based Safety Case Report” as mentioned previously. It should be noted that this technical report assumes a readership with a certain level of technical expertise and background knowledge of geological disposal.

(4) Organisation of report preparation

For the production of this report, which required input from relevant research institutes and domestic and international experts, the systematic approach illustrated in Figure 1.4-4 was implemented. This ensured that the latest findings and technical development results were effectively captured, together with technical review and advice from experts outside of NUMO. These efforts were aimed at ensuring the technical quality of this report.

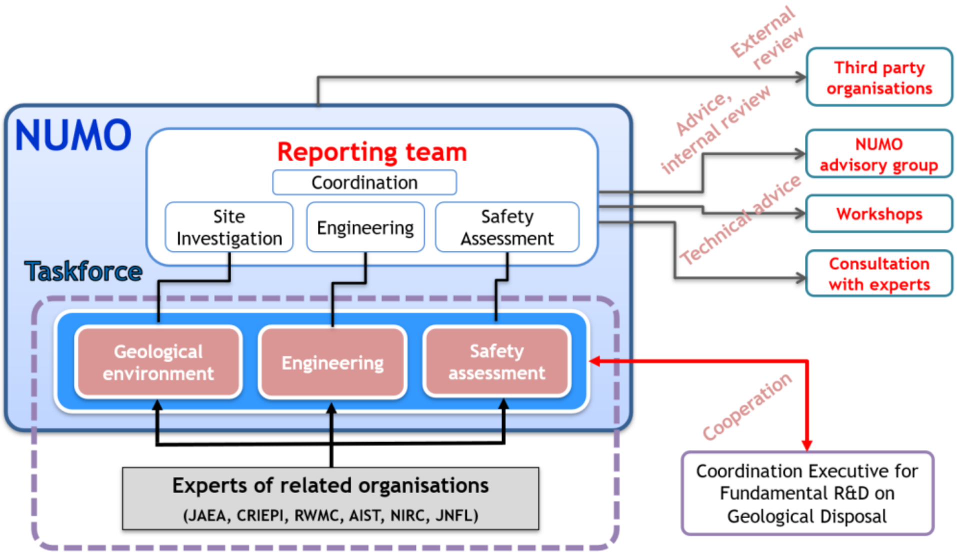

Figure 1.4-4 Overview of safety case report production

In addition, NUMO published the 'NUMO Safety Case Report for Review' in October 2018 and the report was then peer-reviewed by the Atomic Energy Society of Japan (AESJ), in order to obtain an objective evaluation of its technical content. Based on the comments and suggestions from the AESJ review team in December 2019 [17], the report was subsequently revised (resulting in the present document).

(5) Abbreviations

The abbreviations given in Tables 1.4-1 to 1.4-3 are used throughout this report, for laws, report titles and organisations relevant to geological disposal (both Japanese and international). In principle, the units used in this report are SI (SI base and derived units). However, non-SI units are also used as needed. A list of these is given in Table 1.4-4.

Table 1.4-1 International organisations relevant to geological disposal

	Full name	Abbreviation
International organisations	International Atomic Energy Agency	IAEA
	International Commission on Radiological Protection	ICRP
	Organisation for Economic Co-operation and Development/Nuclear Energy Agency	OECD/NEA
	Nuclear Waste Management Organization (Implementer, Canada)	NWMO
	Säteilyturvakeskus (Regulator, Finland)	STUK
	Posiva Oy (Implementer, Finland)	Posiva
	Autorité de sûreté nucléaire (Regulator, France)	ASN
	Agence Nationale pour la Gestion des Déchets Radioactifs (Implementer, France)	ANDRA
	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Implementer, Germany)	BMU
	Gesellschaft für Anlagen und Reaktorsicherheit (Regulator, Germany)	GRS
	Strål Säkerhets Myndigheten (Regulator, Sweden)	SSM
	Svensk Kärnbränslehantering AB (Implementer, Sweden)	SKB
	Eidgenossisches Nuklearsicherheitsinspektorat (Regulator, Switzerland)	ENSI
	Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (Implementer, Switzerland)	Nagra
	Environment Agency (Regulator, UK)	EA
	Radioactive Waste Management, a subsidiary of the Nuclear Decommissioning Authority (Implementer, UK)	RWM NDA
	Nuclear Regulatory Commission (Regulator, USA)	US NRC
	US Department of Energy (Implementer, USA)	US DOE

Table 1.4-2 Domestic organisations relevant to geological disposal

	Full name	Report abbreviation
Domestic organisations	Nuclear Waste Management Organization of Japan	NUMO
	Japan Atomic Energy Agency Previously: Japan Nuclear Cycle Development Institute Before that: Power Reactor and Nuclear Fuel Development Corporation	JAEA JNC PNC
	Radioactive Waste Management Funding and Research Center	RWMC
	Central Research Institute of Electric Power Industry	CRIEPI
	National Institute of Advanced Industrial Science and Technology	AIST
	National Institute of Radiological Sciences	NIRS
	Japan Nuclear Energy Safety Organization	JNES
	Federation of Electric Companies of Japan	FEPC
	Atomic Energy Society of Japan	AESJ
	Nuclear Regulation Authority	NRA
	Japan Atomic Energy Commission	JAEC
	Japan Nuclear Fuel Limited	JNFL

Table 1.4-3 Abbreviated list of key Japanese reports, laws and associated documents relevant to geological disposal

	Full name	Abbreviation
Laws etc.	Designated Radioactive Waste Final Disposal Act	Final Disposal Act
	Law Enforcement Regulations on Final Disposal of Specified Radioactive Waste	Final Disposal Law Enforcement Regulations
	Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors	Nuclear Reactors Regulation Act
	Basic Policy on Final Disposal of Designated Radioactive Wastes	Basic Policy on Final Disposal
	Designated Radioactive Waste Final Disposal Program	Final Disposal Program
	Regulations for the Safe Transport of Radioactive Material*	Transport Regulations
Reports	H12 Project to establish the scientific and technical basis for HLW disposal in Japan – second progress report on research and development for the geological disposal of HLW in Japan	H12 Report
	H17: Development and management of the technical knowledge base for the geological disposal of HLW	H17 Report
	Second progress report on research and development for TRU waste disposal in Japan	TRU-2 Report
	Safety of the geological disposal project 2010 - safe geological disposal based on reliable technologies	2010 Report

*Defined by NRA referring to 'Regulations for the Safe Transport of Radioactive Material 2012 Edition, IAEA Safety Standards Series No. SSR-6'.

Table 1.4-4 SI units and non-SI units used in the NUMO SC

Quantity	Unit system	Unit symbol
Time	SI base unit	s
Length	SI base unit	m
Mass	SI base unit	kg
Thermodynamic temperature	SI base unit	K
Amount of substance	SI base unit	mol
Force	SI derived unit	N
Pressure, stress	SI derived unit	Pa
Energy, work, heat	SI derived unit	J
Power, radiant flux	SI derived unit	W
Potential difference	SI derived unit	V
Celsius temperature	SI derived unit	℃
Radioactivity	SI derived unit	Bq
Dose equivalent	SI derived unit	Sv
Time	Non-SI unit	min
	Non-SI unit	h
	Non-SI unit	d
	Non-SI unit	y
Plane angle, phase angle	Non-SI unit	°
Volume	Non-SI unit	l

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[4] JAEA (Japan Atomic Energy Agency) and FEPC (The Federation of Electric Power Companies of Japan) (2007): Second progress report on research and development for TRU waste disposal in Japan, JAEA-Review 2007-010, FEPC TRU-TR2-2007-01.

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characteristics of geological disposal (summarised by the Geological Disposal Technology WG), Geological Disposal Technology WG, Nuclear Energy Subcommittee, Electricity and Gas Industry Committee, Advisory Committee for Natural Resources and Energy (in Japanese).

[13] METI (Ministry of Economy, Trade and Industry) (2017): Explanation material of the nationwide map of "scientific features" relevant for geological disposal, https://www.enecho.meti.go.jp/en/category/electricity_and_gas/nuclear/rwm/pdf/explanation_material.pdf (accessed 2021-01-12).

[14] IAEA (2012): The safety case and safety assessment for radioactive waste, Specific Safety Guide, IAEA Safety Standards Series, No. SSG-23.

[15] OECD/NEA (2004): Post-closure safety case for geological repositories, NEA No. 3679.

[16] OECD/NEA (2013): The nature and purpose of the post-closure safety cases for geological repositories, NEA/RWM/R(2013)1.

[17] AESJ (Atomic Energy Society of Japan) (2019): Report of the Special Review Committee on the NUMO safety case, Special Review Committee on the NUMO Safety Case, https://www.numo.or.jp/en/what/pdf/The_review_of_the_NUMO_safety_case.pdf (accessed 2021-01-12).

2 SAFETY CONCEPT

As described in Section 1.4.2, NUMO's current strategy for developing the safety case describes the basic approach to ensuring safety, and shows how it intends to achieve safe geological disposal during each phase defined in the implementation programme [1]. In this chapter, after first setting out the requirements to be considered at the current stage of geological disposal planning, the technical considerations for site characterisation, repository design and safety assessment are described. Finally, the required management concepts and tools for integrating this work in an effective and quality assured manner are described and the structure of the following, more detailed documentation is summarised.

2.1 Requirements to be considered when planning geological disposal in Japan

The required safety features for geological disposal of radioactive waste at specific sites depend on the characteristics of the waste and the specifications in laws and regulations, as outlined in this section.

2.1.1 Radioactive waste subject to geological disposal

As mentioned in Section 1.2, radioactive waste for geological disposal in Japan includes vitrified HLW and TRU waste[1] (see Supporting Report 2-1 for details of the definition of these "designated wastes"). Immediately after production of HLW, both activity and the resulting thermal output are significant, so the waste is first safely stored for about 30 to 50 years before it can be accepted for disposal. In addition, TRU wastes are solidified, sealed and stored in containers before disposal, as specified in the Basic Policy on Final Disposal.

In order to carry out the design and safety assessment of the repository, further information on the amount of waste generated and its characteristics are required, as provided below.

(1) Basic information on vitrified HLW

There are four sources of HLW: vitrified waste reprocessed and returned from overseas (by Orano (formerly AREVA NC) in France and Sellafield Ltd. (formerly BNFL) in the UK) and vitrified waste produced in Japan by JAEA and JNFL (Japan Nuclear Fuel Limited). Table 2.1-1 shows the standard specifications of such HLW [2] [3]. Further details of the properties of HLW are given in Supporting Report 2-2.

[1] The definition of TRU waste to be disposed of in a geological repository is slightly different according to the Final Disposal Act and the Nuclear Reactors Regulation Act. The treatment of this is summarised in Supporting Report 2-1.

Table 2.1-1 Standard specifications of HLW and fabrication canisters[2] and number currently in storage (based on [2], [3], [4] [5], [6], [7])

Producer	JNFL	JAEA	Orano	Sellafield Ltd
Total radioactivity (Bq - at time of production)	$\beta, \gamma \leq 2.17 \times 10^{16}$ $\alpha \leq 1.29 \times 10^{14}$	$\beta, \gamma \leq 1.5 \times 10^{16}$ $\alpha \leq 2.6 \times 10^{14}$	(Representative) $\beta, \gamma \leq 2.8 \times 10^{16}$ $\alpha \leq 1.4 \times 10^{14}$	(Representative) $\beta, \gamma \leq 4.5 \times 10^{16}$ $\alpha \leq 3.5 \times 10^{14}$
Thermal power (kW)	≤ 2.3 (at time of production)	≤ 1.4 (at time of production)	< 2.0 (at time of transportation)	< 2.5 (at time of transportation)
Dimensions of fabrication canister (mm)	Height: 1,340 Outer dia.: 430 Canister thickness: 6	Height: 1,040 Outer dia.: 430 Canister thickness: 6	Height: 1,340 Outer dia.: 430 Canister thickness: 5	Height: 1,340 Outer dia.: 430 Canister thickness: 5
Weight of filled HLW canister (kg)	500	380	492	550
No. of HLW canisters in storage (December 2020)	346	316	1,310	520

Information on the evolving heat generation rate and radioactivity inventory of waste from the time of receipt in a repository is necessary for repository design and safety assessment. In this report, such properties are established based on the following assumptions, with details given in Supporting Report 2-3.

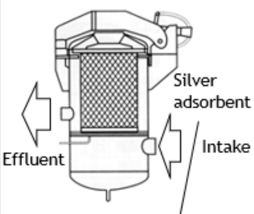
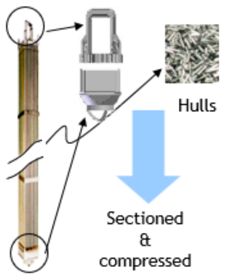
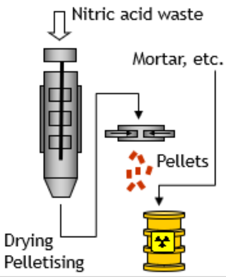
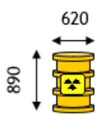
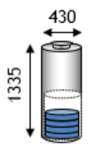
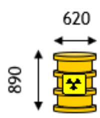
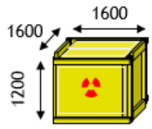
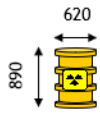
- When the JNFL reprocessing plant is operational[3], the generated HLW from existing spent fuel (SF) or the SF generated by future nuclear power plants will account for the majority of the total inventory. Therefore, in this report, as in the H12 report, JNFL specifications of typical vitrified HLW [8] will be used as a reference for repository design and safety evaluation. This can be used to define the thermal output and radionuclide (RN) inventory of the waste at the time of disposal.
- The standard specification of SF is that used for the design of the JNFL reprocessing plant (fuel type PWR, burnup 45,000 MW days, initial enrichment 4.5%, specific power 38 MW, initial cooling period four years until reprocessing[4]) in order to calculate the thermal output and RN inventory.
- The storage period after fabrication of the HLW until it is received at the repository is expected to range from 30 to 50 years according to the Basic Policy on Final Disposal, but it is difficult to be more specific at the present stage. For this reason, two storage periods, 30 and 50 years, are considered.

[2] N.B. During the reprocessing of spent fuel, liquid HLW is calcined and then vitrified within a fabrication canister – together referred to as a HLW canister for subsequent handling.
[3] Construction of the JNFL reprocessing plant is planned to be complete in the first half of FY 2022 [9]. 346 HLW canisters are in storage as of December 2020 (produced during active tests of the reprocessing plant).
[4] JNFL is currently planning to specify an initial cooling period 15 years or more until reprocessing [10]. For studies of repository design and safety assessment in this report, a cooling period of 4 years is considered to be the current standard specification for spent fuel. The study regarding the influence of these different cooling periods on the inventory is shown in Supporting Report 2-3.

(2) Basic information on TRU waste

TRU wastes are low-level radioactive wastes generated during the operation and decommissioning of SF reprocessing facilities and MOX fuel plants at JAEA and JNFL, and during the reprocessing of SF outsourced to other countries. These wastes include various types of materials such as metal, mortar, bitumen etc., which differ in their form and RN content. For this reason, wastes are classified into four groups based on their characteristics [11] [12], as shown in Table 2.1-2, referring to the TRU-2 report [13][5].

Table 2.1-2 Group classification and characteristics of TRU waste (expanded from NUMO, 2011 [12])

Group	1	2	3	4	
				Low heat	High heat
Description	Iodine adsorbent  Adsorbent to remove radioiodine	Hulls & Ends 	Concentrated solution, etc. 	Organic waste  Rubber gloves (incineration / compression) Non-combustible waste  Tools  Metal pipes	
Image of waste form (unit: mm)	 Drum - 200 l	 Canister	 Drum - 200 l	 Box container	 Drum - 200 l
Features	• Radioiodine (I-129) • Cemented waste form	• Relatively high heat • Radiocarbon (C-14)	• Contains nitrate • Solid waste • e.g. mortar or bitumen	• Incineration ash • Non-combustibles • Solidified waste with mortar, etc.	
Expected volume generated (m³)	319	5,792	5,228	5,436	1,309
Thermal power at time of production	< 1 (W/drum)	< 90 (W/canister)	1 (W/drum)	16 (W/drum)	210 (W/drum)

The following characteristics of each group should be taken into account in the design of a repository and associated safety assessment.

- Group (Gr.) 1 comprises the silver adsorbent used to capture off-gas iodine, which is immobilised with mortar and has extremely low heat output. It contains a significant amount of radioactive iodine (I-129), a long-lived radionuclide with assumed high solubility and low sorption.

[5] The TRU wastes generated in the reprocessing process of spent fuel in France have been returned as "CSD-B", containing vitrified residues from low-level enriched liquid waste, and "CSD-C", containing solidified materials such as hulls. These were included in Gr.2, which has a similar waste form, considering convenience of operation [12]. The TRU wastes generated in the course of reprocessing in the UK will be substituted for vitrified high-level radioactive wastes with equivalent radiation effects [14], and these wastes will be included in the HLW inventory.

- Gr.2 comprises compressed metal cladding stripped from SF (hulls and ends), sealed in a stainless steel canister. Its thermal output is relatively high and it contains a large amount of radioactive carbon (C-14), which is an intermediate half-life nuclide with assumed high solubility and low sorption.
- Gr.3 results from the solidification of liquid waste generated during reprocessing. It is conditioned in a matrix of bitumen or mortar and has a relatively low heat output. It contains nitrate, which can affect the engineered barrier and host rock containment.
- Gr.4 consists of miscellaneous wastes generated during reprocessing and MOX fuel fabrication, which are solidified or encapsulated in mortar, etc. There are two types of such waste: one with relatively low (Gr.4L) and the other with relatively high (Gr.4H) thermal output [11].

More details on the characteristics of TRU waste are provided in Supporting Report 2-4. The thermal output and RN inventory at the time of waste production were documented by NUMO in 2011 [12] [15]. Further, since the TRU storage time before disposal is not defined, in line with the TRU-2 report [13] thermal output and RN inventory are calculated at 25 years after production [9] [11], which is taken as the assumed emplacement time (see Supporting Report 2-3 for more background).

The thermal output and radioactivity inventory of HLW and TRU waste described above will be regularly reviewed to reflect production, storage volume and storage period of based on the evolution of nuclear energy utilisation and the operational status of reprocessing facilities.

(3) Waste acceptance criteria

In order to construct a safe repository, NUMO will establish the acceptance criteria for HLW and TRU waste, based on the progress of site selection and the design of the repository, with sufficient time before the application for the project licence. The relevant laws and regulations that should be taken into account in setting these acceptance criteria, and the acceptance criteria for HLW in similar projects for reference, are documented in Supporting Report 2-5. It is understood that part of the HLW is already vitrified, whereas most of the TRU waste is not yet conditioned. There is no decision as yet on how to condition these wastes and whether additional conditioning (e.g. of bituminised waste) or repackaging would be needed. Such potential needs will strongly depend on what repository concepts are finally selected.

(4) Required repository capacity

As shown in Table 2.1-1, as of December 2020 a total of 2,492 HLW canisters are stored safely at reprocessing facilities at both JNFL in Rokkasho-mura, Aomori prefecture, and JAEA in Tokai-mura, Ibaraki prefecture. However, it should be noted that spent fuel, corresponding to approximately 25,000 canisters of HLW, has already been generated. According to the “Plan for the Final Disposal of Designated Radioactive Wastes” (hereafter the “Final Disposal Plan”) published in 2008, about 3,231 m^3 of TRU waste is stored at both JAEA and other facilities in Japan as of 2007.

The Final Disposal Plan requires that a disposal site can accommodate of the following volumes of waste:

- HLW: 40,000 canisters or more (to be disposed of at a rate of about 1,000 per year).

- TRU waste: ≥ 19,000 m^3.

It is difficult to estimate the total generation of radioactive waste to be disposed of because such numbers depend on future nuclear power policies to be established in Japan. In this report, based on the above, 40,000 canisters of HLW is assumed for repository design and safety assessment. For TRU waste, the total estimated amount generated in Table 2.1-2 is 18,084 m^3, so this is modified to obtain a disposal volume 19,000 m^3 or more specified by the Final Disposal Plan.

(5) Co-disposal of HLW and TRU waste

There are clear practical advantages of co-locating repositories for HLW and TRU waste – for example in terms of reducing required efforts for site characterisation and sharing of some infrastructure, although the potential interactions between these wastes needs to be considered [12]. With a focus on safety, assuming that conclusions would be applicable also to separate disposal facilities, in this report co-located repositories for HLW and TRU waste are assumed.

2.1.2 Required safety functions of the repository

(1) Safety features of geological disposal

As described in Section 1.1, a deep geological setting has the function of physically isolating waste from the biosphere whilst also suppressing release and migration of RNs contained in groundwater. A repository comprises both engineered and natural barriers in a suitable geological setting, which function together to safely isolate the radioactive waste from the human environment, and contain RNs until long after closure, during which time most will have decayed and any residual radiological risk is acceptably low. Such a safety concept is based on a multi-function/multi-barrier system and is common to all advanced national programmes (in addition to being the international standard), and is explicitly specified in the Basic Policy on Final Disposal.

The basic concept of ensuring post-closure safety by geological disposal can be specified in terms of the key safety functions of “isolation” (removal from humans/the biosphere) and “containment”[6]. These functions can be related to the roles of different components of the repository system in ensuring safety. In recent years, this concept has proven important for directly demonstrating the link between conceptual explanations of the repository as mentioned above and practical actions, such as repository design and safety evaluation, within the framework of a safety case [16] [17].

In order to ensure safety during construction and operation to the point of closure, the safety features required are generally similar to those necessary for other nuclear facilities or underground structures. The post-closure, multi-barrier safety features described here are fundamentally the same as those commonly used in other repository concepts for HLW and TRU waste developed in other national programmes.

[6] In this report the word “containment” includes both complete containment and the ability to constrain/retard releases. In many other safety cases the latter is called “retention”. See also further discussion in this section. N.B. This footnote is not included in the Japanese version of the report.

(2) Required operational safety functions

During the operational phase, safety functions ensure the safety of local residents and repository workers from both radiation risks and hazards other than those associated with radiation.

Those safety functions related to radiation protection during the operational phase are summarised in Table 2.1-3. Operational containment refers to the confinement of radioactive material in a restricted area to prevent its release outside the facility during the operational period of handling the waste until closure.

Table 2.1-3 Required operational radiological safety functions (based on NUMO, 2011 [18])

Basic concept	Safety function	Description
Containment during operation	Prevention of leakage of RNs from waste	Complete containment[7] of the waste during the operational period
	Prevention of release of RNs from the repository	Prevention of release of radioactive material due to any perturbations during waste handling operations
Radiation shielding	Reduction of radiation dose	Effectively complete shielding of external radiation from the waste

Containment of radioactivity within the waste results primarily from the waste conditioning and packaging, complemented by the robust systems used to transport waste to and within the repository.

Although transport, storage and handling systems are designed to minimise the risk of perturbations, these can never be completely precluded and hence a further safety function is containment within the surface or underground facilities of the repository in case of any accident that breaches the waste package. For such cases, containment measures will be established for all relevant facilities after evaluation of both the probability of perturbations that could lead to leakage of radioactivity and the consequences of such an event.

Even when RNs are contained within the waste package, there is always a potential risk due to the penetrating nature of particular radiation (gamma rays and high energy neutrons). Any such health hazard to workers is reduced by assuring that sufficient shielding is present to reduce external radiation dose rates to acceptable levels, and that this is complemented by appropriate use of monitored, radiation-controlled zones and monitoring of worker doses. The layout and design of the repository assures that there is no dose to surrounding populations from this source.

Incidents not involving radiation, referred to as industrial accidents, include those impacting the public around the facility and those impacting only the workers engaged in the construction, operation, and closure of the repository. The former can include secondary impacts around the facility due to fire or other incidents (smoke, fumes, etc.) and also traffic accidents involving off-site vehicles during the construction and operation of the facility.

[7] Complete containment is generally assured when the container and/or matrix is intact. N.B. This footnote is not included in the Japanese version of the report.

With regard to industrial safety of workers, the repository is designed to prevent accidents from developing and ensuring maintenance of a healthy working environment during the period from the geological survey, construction, operation until final closure of the site. The safety functions related to industrial safety of the repository during the pre-closure phase are shown in Table 2.1-4.

Table 2.1-4 Required operational occupational safety functions (based on NUMO, 2011 [18])

Basic concept	Safety function	Description
Prevention of industrial accidents	Prevention of occurrence and propagation of incidents	Establish counter-measures to prevent occurrence of events which could lead to work-related accidents
	Evacuation routes established in case of accidents	Safe havens and evacuation routes established for all relevant accident scenarios
Maintenance of healthy working environment	Maintain conditions appropriate to worker health and safety	Ensure comfortable and healthy working conditions

Prevention of industrial accidents includes safety measures to reduce the impact of natural perturbations caused by earthquakes, tsunamis, pyroclastic flows, landslides, etc., as well as possible operational incidents such as rock-falls, fires and explosions. Included here are also measures taken to respond to incidents (so that they do not develop further to accidents) and protective actions in the event that accidents do occur, such as safe underground evacuation routes. Special activities related to maintaining a healthy working environment are particularly associated with controlled surface or underground facilities, where temperature, humidity, particulate concentration, noise level, etc. are set at levels established to be comfortable for workers.

Required pre-closure safety functions can be subdivided in terms of safety features of repository design components, as discussed further in Section 4.2.4 (1). The safety functions to be assigned to each component and the design requirements for the safety of the repository before closure are given in Chapter 4.

(3) Required post-closure safety functions

After closure, the repository will have isolation and containment roles, as summarised in the safety functions shown in Table 2.1-5.

Table 2.1-5 Required post-closure safety functions (based on IAEA, 2011 [19])

Basic Concept	Safety function	Description
Isolation	Protection from significant effects of natural perturbing phenomena	Assuring sufficient depth to avoid risks due to surface perturbations for the time when waste toxicity is high
	Reduction of the likelihood of human intrusion	Emplacement deep in a suitable geological environment reduces the risk of inadvertent human intrusion
Containment	Restriction of RN leaching	Retention[8] within the waste package for the period of highest toxicity and slow release thereafter, assured by hydrogeology and geochemistry of the deep underground setting
	Restriction of RN migration	Delay and reduction of releases to the biosphere due to retardation during geosphere transport

In terms of isolation, the assurance of protection from geological perturbations is particularly important in Japan due to its location relative to active tectonic plates, which results in significant potential for volcanism, fault movement and uplift/erosion at some locations. Careful siting and disposal at sufficient depth is thus required to ensure that the selected geological setting would not be significantly perturbed over the assessment timescale.

In addition, the geological environment should contribute to reduction of the risk of anthropogenic perturbations – predominantly by excluding areas containing mineral resources that might be exploited in the future, when knowledge of the repository has been forgotten. The depth of disposal is also a factor here, ensuring that it is sufficient to avoid potential impacts due to conventional civil engineering activities at times when there is no longer institutional control of the disposal site. These safety functions related to isolation are one role of the geological environment, which will be confirmed through investigation and evaluation during site characterisation, as discussed further in Chapter 3.

Containment will be ensured by safety functions that involve, firstly, containment of most RNs in and around the engineered barriers for an extended period and, secondly, restriction of the rate of RN release thereafter. In terms of containment of RNs, the low water flow at depth and suitable geochemical conditions (e.g. chemically reducing groundwater) support the longevity of containers that completely contain the waste. This ensures a decrease in toxicity and thermal output due to radioactive decay of shorter-lived isotopes [17] and, thereafter, together with buffer, backfill and plugs, limits the rate of RN release from the engineered barriers for the expected natural barrier properties.

After release from the engineered barriers, the site geology plays further roles in delaying and reducing RN release concentrations due to slow groundwater flow rates, long transport paths, retardation and dispersion during transport (see Chapter 3, Section 3.1.1 (2)) and dilution at the geosphere-biosphere interface.

The safety functions assigned to each component and the design requirements for the long-term post-closure safety of the repository are discussed further in Chapter 4.

[8] Here the definition of retention means highly effective immobilisation (containment) within a specific barrier or zone, but allows for trace releases. N.B. This footnote is not included in the Japanese version of the report.

(4) Spatial scales over which safety functions apply

The size of the planar repository area (footprint) for disposal of 40,000 HLW canisters was estimated in the past to be about 3 km × 2 km and that for 19,000 m^3 of TRU waste to be about 0.5 km × 0.5 km, with the surface facilities requiring about 1 × 1.6 km, assuming co-disposal [12]. Although the actual footprint will depend on site geological and environmental conditions, on the basis of past study cases this would be in the order of a few km^2, even assuming co-disposal.

Depending on the geological setting, the surface facility may be directly above or somewhat displaced from the disposal panels, which themselves may lie at a set depth (below 300 m and up to depth of a km or so) or be distributed between multiple levels within this range. Taking into account the barrier roles of surrounding rock, the investigations to confirm the isolation and containment functions would cover an area of several km × several km and a depth of around 1 km or more.

(5) Safety function timescale

Considering that the radioactivity of the waste remains significant for an extremely long time (Figure 1.1-1), it is necessary to consider the timescales over which repository safety functions should operate. The disposal system will be put in place during the construction and operational phases and then slowly evolve post-closure, with recovery of the original saturated hydrogeological and reducing chemical environment, long-term degradation of the engineered barriers and gradual alteration of the geological environment due to tectonic movements. It is thus necessary to set the repository safety functions considering such temporal changes, as discussed below.

The time required for the disposal project will depend on site environmental conditions, but can be roughly estimated as follows: 20 years for site investigation, 10 years for repository construction, 50 years for operation, and 10 years for repository closure [18]. During the period from repository construction until closure, the expected radiological safety and general occupational health and safety functions, as given in Tables 2.1-3 and 2.1-4 respectively, will be assured by appropriate site selection, design, construction and operation of the repository, and confirmed by operational safety assessment.

Following backfilling and closure of the repository, any open void space will gradually re-saturate and trapped oxygen will be consumed, to allow recovery of original reducing conditions. The extent of the transient phase in the natural and engineered barrier system (EBS) depends on the amount of heat generated and the specification of particular engineered barriers, with past studies suggesting periods of several tens to a few hundred years [12][20]. When considering the potential for gas generation, these times could be even longer. Quantification of the performance of the multi-barrier system for high thermal output waste during the initial transient period is complex and, to reduce uncertainties, it is thus preferable that the EBS has the function of excluding contact between the waste and the groundwater during this period, so that release and transport of RNs do not have to be assessed. However, it should be noted that this may not be the case for Gr.4H – releases could occur before the thermal transient has passed.

Only after the complete containment function is lost, will waste come into contact with groundwater and RNs begin to dissolve. In practice, the containment functions of the EBS will gradually evolve, with changes in performance being very slow and the retardation function of the engineered barriers lasting for a very long time, if the favourable geological environment persists. In a properly selected geological environment with favourable characteristics (e.g., low groundwater flow), it is considered that the migration-inhibiting function of the engineered barriers can be assured for a very long period of time, especially as the multiple barriers provide robust performance even when the functions of some individual components are degraded. During this time, most RNs will remain within, or in the vicinity of, the engineered barriers s. Furthermore, any RNs released will be retarded further in the geological environment. Thus, during site selection, it will be important to verify (in addition to its isolation functions) that the long-term retention function of the geological environment is assured. However, it will still be necessary to evaluate the transport behaviour of RNs from the EBS to the surface, and to assess the impact (dose) of RNs released to the biosphere, in order to confirm whether the safe functioning of the repository can be ensured.

Continuous plate tectonic movement which causes phenomena such as volcanic activity, faulting, and uplift and erosion, is expected to proceed at a uniform speed in one direction, and the occurrence of such natural phenomena and their effects on the geological environment are likely to continue for a period of up to 100 ky [21] [22] (see Supporting Report 3-1). Such an assumption, which was also in the H12 Report [20] and reviewed by the Government [23], is considered to be acceptable [24], and its validity has been reconfirmed in the latest compilation of findings [25] since the H12 Report [20]. Therefore, it is considered that the favourable characteristics of the deep geological environment at appropriately selected sites can be maintained, avoiding significant effects of perturbing phenomena, and that the long-term isolation and containment functions expected of the geological environment can be ensured (see Section 3.1).

Between around 100 ky to 1 My, evolution of the geological environment characteristics will be assessed by models or extrapolations of paleo-geological observations, based on evidence for the long-term continuity of events and processes governed by tectonic plate movement over the last several million years [26] [27]. Current tectonics show a generally consistent picture over a period of several 100 ky to 1 My, although regional differences may be found [22] [28]. The safety of a future repository can thus be evaluated on the basis of this knowledge base, bearing in mind the inherent uncertainties associated with geological evolution over such a long period of time.

The occurrence of natural perturbing phenomena and their effects on the geological environment at a site can be assessed, together with their uncertainties, using a combination of extrapolation, analogy and probabilistic methods (see Section 3.2.3 (2)). In areas that have not been significantly affected by disruptive natural phenomena, it has been found that hydrogeological and chemical conditions favourable for geological disposal have been maintained for more than a million years [29] [30], despite the effects of inevitable fault movement, uplift, erosion and sea-level change (see Section 3.1.3 (2)). Such paleo-hydrogeological evidence indicates that there is little likelihood of sudden or abrupt changes in the characteristics of the deep subsurface environment, because disturbances are constrained by the inherent buffer functions of the geological environment [31]. By integrating these findings with the results of the previous assessments, it can be argued that the expected isolation and containment functions of the geological environment are likely to be maintained for several hundred thousand years or more and this can be confirmed by rigorous site-specific assessment. In addition, it is necessary to assess the transport behaviour of RNs in the geosphere, taking into account associated uncertainties, and to assess the effects of radiation on the biosphere (dose), in order to confirm that the required safety functions of the repository can be assured.

For longer timescales, beyond a few hundred thousand to a million years, the uncertainties associated with the assessment of the required safety functions of a repository are even greater. Both the scientific evidence for the occurrence and impacts of natural perturbations and the persistence of driving tectonic plate movements is inherently more limited. Over such very long timescales, it is less useful to assess future human safety by calculating doses, and more important to discuss safety in terms of other indicators, such as the relative toxicity of remaining radioactivity in the repository and that naturally occurring in the host rock.

The basic concepts for site selection, repository design, and safety assessment are described in detail in Sections 2.2, 2.3 and 2.4 respectively, taking into account such safety functions for different timescales.

2.1.3 Meeting the requirements of laws and regulations

Geological disposal of radioactive waste in Japan is regulated by the Final Disposal Act, the Basic Policy on Final Disposal and the Final Disposal Plan set by METI. In addition, safety regulations will be separately determined by the Nuclear Regulation Authority (NRA), which is the regulatory body. NUMO is responsible for formulating and implementing the project in accordance with these laws and regulations.

(1) Phased implementation

Figure 2.1-1 illustrates the stepwise site selection process as regulated by the Final Disposal Act. This involves Literature Surveys (LS) of volunteers, selection of Preliminary Investigation Areas (PIAs), from these, selection of Detailed Investigation Areas (DIAs) and, finally, a site for application for a repository construction licence (which also covers the operational phase).

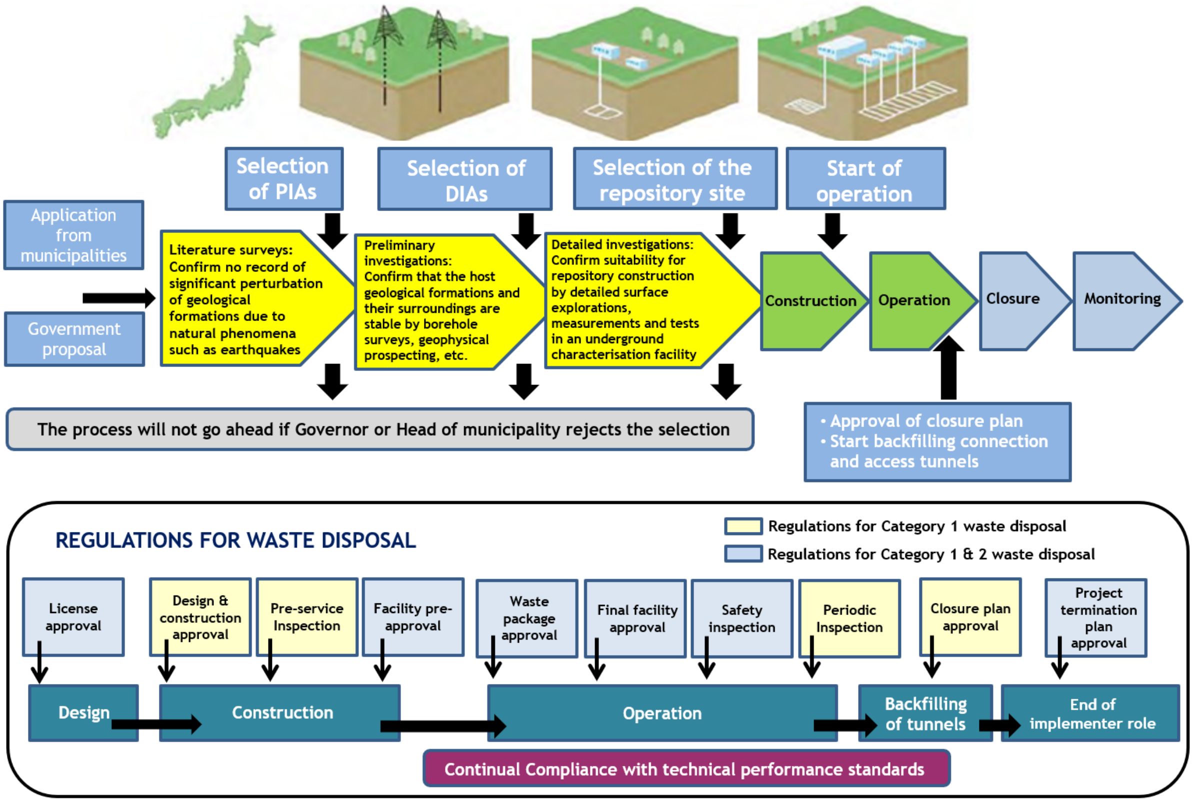


Figure 2.1-1 Japan's phased implementation process for geological disposal (Based on Advisory Committee for Natural Resources and Energy, 2014 [32])

When selecting an area to move to the next stage of investigation, it has to be ensured that the selection requirements (statutory requirements) specified in the Final Disposal Act (Table 2.1-6) are met. In addition, it is necessary not only to satisfy such statutory requirements, but also to comply with any requirements for ensuring safety that will be specified by regulatory bodies in the future. Progressing from one investigation stage to the next involves intensive interaction with stakeholders, in particular aimed at obtaining the understanding of the region.

For implementation, METI will determine the acceptability of sites selected for investigation, taking account of opinions of the prefectural governor and the mayor of the municipality with jurisdiction over the site. Also, NUMO must provide the results of each investigation stage in the form of a report for review by relevant prefectures, and, if issues are raised, it is stated that sites should be selected with consideration of these. Thus, NUMO will not proceed to the next siting stage if the mayor of the municipality or prefectural governor is opposed, regardless of the result of the investigations.

In order to increase the transparency of the selection process and enhance safety-related considerations, NUMO will establish selection criteria for both the preliminary investigations (PIs) and detailed investigations (DIs) to judge eligibility, based on the statutory requirements. The selection criteria established will be announced before the start of each survey stage.

Table 2.1-6 The selection requirements specified in the Final Disposal Act

Siting stage	Selection requirements
Selection of PIA (during LS)	• There should be no record of significant movement in geological formations due to earthquake or fault activity, igneous activity, uplift, erosion and other natural phenomena • The possibility of significant movement in the future due to earthquake or fault activity, igneous activity, uplift, erosion and other natural phenomena should be small • There should be no record of unconsolidated Quaternary deposits at appropriate depths • There should be no record of mineral resources that are economically valuable
Selection of DIA (during PI)	• The host geological formation has not been subject to significant geological change for a long period of time due to natural phenomena such as earthquakes • The host geological formation is suitable for excavation • If there are active faults, fracture zones, or groundwater flowing in the subject stratum, etc., there is little risk that these will adversely affect the tunnels and other underground facilities • Other matters specified by an Ordinance of the Ministry of Economy, Trade and Industry
Selection of repository site (during DI)	• The underground facilities are not likely to be subjected to abnormal pressure in the target formation, and its physical properties are expected to be suitable for repository implementation • The underground facilities are not likely to be subjected to abnormal corrosive effects in the target geological formation, and the chemical properties are expected to be suitable for repository implementation • There is no risk of groundwater flow interfering with the functioning of the underground facilities • Other matters specified by an Ordinance of the Ministry of Economy, Trade and Industry

For the LS phase, in 2002 NUMO published siting factors for selecting PIAs [33]. Since then, as described in Section 1.3, the Nationwide Map was published which, together with the associated reports produced by the Geological Disposal Technology [21][34] and Radioactive Waste Working Groups (WGs) [32], provides confirmation on how to proceed with the LS stage and subsequent site selection. If a municipality applies for a LS, this will be initiated based on the report of the WG on Geological Disposal Technology [34] and an established procedure [35].

After the selection of a repository site, NUMO will move to a licensing process, starting from project permitting, through subsequent safety reviews for construction, operation, closure, management after closure and, finally, discontinuation of any management role in accordance with the Act for the Control of Nuclear Source Material, Nuclear Fuel Materials and Nuclear Reactors (hereafter the "Nuclear Reactors Regulation Act"). After discontinuation of NUMO's role, the Japanese government will assume all responsibility for site access control, record-keeping, etc[9]. Currently, project implementation is estimated to

[9] Regarding "post-closure monitoring" illustrated in Figure 2.1-1, there is no established scientific rationale for continuing monitoring after the completion of closure measures and associated confirmation of long-term safety.

take over 100 years. Therefore, NUMO identifies intermediate milestones and implementation items to achieve the goals of each phase, based on an overview of the total project. This allows required technology development to proceed in a systematic and stepwise way. In the 2010 technical report [18], a project implementation plan for ensuring safety and development of required technology was presented in the form of a road map.

(2) Assuring reversibility and retrievability

The OECD/NEA has compiled an international assessment of disposal concepts and the current status in terms of reversibility and retrievability [36]. Reversibility is defined as a means of leaving options open for future generations and providing flexibility in waste management, thus leaving the possibility open to reverse decisions if required. In addition, this option is also considered to increase confidence in the implementation process. Retrievability is a technical measure to provide reversibility of waste emplacement, in particular the ease and safety of such a reversal, were it required. However, any increase in social acceptance of geological disposal resulting from technical modifications to ease waste retrieval needs to be balanced against both a potential decrease in operational or post-closure performance and financial costs. Thus, efforts to improve reversibility and retrievability will require trade-offs with other fundamental project requirements, which differ depending on the boundary conditions of different national programmes [36].

Also, on the basis of such international debates, in Japan there has been discussion on the appropriate level of reversibility and retrievability for geological disposal projects – for example, by the Nuclear Safety Commission (2000) [37] and the Advisory Committee for Natural Resources and Energy (2008) [38]. There is a consensus that it is fundamentally possible to recover waste until repository closure but, in order to carry this out safely and efficiently, adopting a design that explicitly includes this functionality is considered important. As a result, NUMO will develop designs that maintain practical retrievability until the closure plan is approved [18]. As noted by the Radioactive Waste WG [33], this provides an option to review and include future generations in decision-making related to final disposal. Further, in 2015, the revision to the Basic Policy on Final Disposal specified that reversibility and retrievability should be assured until closure of the repository, in order to give future generations the ability to implement an improved disposal concept should one arise. Thus, the government and various research institutes conduct studies on the effects of maintaining such retrievability until final closure for all designated radioactive wastes.

NUMO is aware that assessing reversibility and retrievability for such a long project period has to consider the possibility of changes in social conditions, policies and stakeholder requirements. As the implementing agency, it is thus important to ensure the robustness and flexibility of NUMO’s organisational system, including considering the human and economic resources required.

(3) Safety regulations

Basic policy on the formulation of safety standards and guidelines for geological disposal of radioactive waste was issued by the Nuclear Regulation Authority [37], noting that it would be important to formulate required detailed safety standards and guidelines in steps, in

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However, monitoring may be carried out as necessary to improve public confidence in the geological disposal system [18].

response to the progress of site selection, site-specific situations and developments of science and technology. In the amended Nuclear Reactors Regulation Act (2007), a regulatory framework was established in accordance with progress of the project, as shown in Figure 2.1-1, involving obtaining a permit for the implementation of the project; authorisation of design and construction methods and the closure plan; and regular reviews of the implemented repository (safety reviews). The 2011 accident that occurred at TEPCO's Fukushima Daiichi Nuclear Power Plant has resulted in a review of the entire safety regulatory regime in the nuclear industry: a major revision of the Nuclear Reactors Regulation Act was carried out in 2012 and regulations concerning measures to prevent serious accidents have been implemented for nuclear facilities.

In a revision of the Nuclear Reactors Regulation Act in 2017, a system has been established to limit the underground disturbance of land above and around the repository. Currently, the Nuclear Regulatory Authority is developing new regulatory standards that are expected to be available at the time of selection of PIAs and will be extended to cover later project milestones. NUMO will follow such developments together with relevant international trends to ensure the availability of the necessary technology to be able to respond appropriately.

With regard to the environmental impact aspects of the geological disposal project, it should be noted that, as currently specified, a repository based on the Final Disposal Act is not subject to the Environmental Impact Assessment Act [39]. Nevertheless, in each phase of the investigation, environmental impacts will be assessed and NUMO will take all actions required to protect the environment around the repository.

Based on the requirements noted in Sections 2.1.1 to 2.1.3, Section 2.2 expands on site selection, Section 2.3 on design of the repository, Section 2.4 on safety assessment and, finally, Section 2.5 on the management tools needed for effective implementation of the programme.

2.2 Site selection strategy

Site selection aims to ensure that the geological setting provides the key safety functions of isolation of radioactive waste from the human environment, ensuring that engineered and natural barriers form an effective multi-barrier system to ensure RN containment and avoiding or preventing the effects of natural perturbations on the safety of construction and operation of the repository. The long-term stability of the geological environment is a key factor, assured by extrapolating site-specific geological evolution from the past to the present and thus build understanding of how it will develop in the future.

2.2.1 Siting aspects to ensure operational safety

The integrity of the repository needs to be maintained in order to secure its operational safety functions. Factors that influence the integrity of both underground and surface facilities include natural hazards, such as earthquakes, tsunamis, pyroclastic flows and landslides. In addition, factors such as rock-falls could impact underground facilities. These will be evaluated with respect to the legal requirements to exclude areas with:

- Unconsolidated Quaternary sediments at a depth of 300 m or more, considered to pose a problem for construction, maintenance and operation of the underground facilities.

- Likelihood of perturbing events such as rock bursts, significant flooding, gas inflow, etc., which influence the practicality and safety of construction and operation over a repository lifetime of about a century.
- An unacceptable likelihood that major natural perturbations, such as tsunamis or pyroclastic flows, could occur.

After recognising the level and extent of the possible influences at a proposed site, engineering measures will be considered based on those already developed for related nuclear facilities, underground civil engineering structures, etc. In cases where significant perturbations are likely, and these cannot be managed by engineering counter-measures should they occur, the location would be excluded from further investigations.

2.2.2 Siting aspects to ensure post-closure safety

(1) Assuring isolation functions

Features that assure the isolation of waste in a repository from the human environment are the depth below the surface ensuring siting within a stable rock formation and the absence of natural resources that could lead to inadvertent human intrusion. Factors that could impair isolation include uplift/erosion and magma intrusion, the extent and probability of which will be very site specific.

In order to acquire sufficient information about such perturbing phenomena, natural events and processes with the possibility of impairing the isolation function are investigated over wide areas (approximately tens of km × tens of km) surrounding any site being investigated. Areas with risks of significant perturbations over the next 100 ky are excluded. From this wide area, based on literature review and site investigations, a potential site with minimal probability of such hazards will eventually be selected to host the repository (several km × several km). It also has to be shown that the risk of human intrusion is low, due to the absence of potentially exploitable natural resources. If it cannot be concluded that a sufficiently large potential repository construction site is free from such risks, even considering tailored repository concept options to reduce the areas of favourable rock required (e.g., compact or multi-level repositories), the location would be excluded from further consideration.

(2) Assuring containment functions

The geological environment is intended to effectively confine RNs, i.e., most RNs remain or decay away within the repository EBS and its vicinity over relevant timescales. The small fraction of RNs that migrate to the biosphere are released in sufficiently low concentrations that they do not have a significant radiological impact on humans or the environment, being well below the permitted levels. Such a containment function results from the mutually complementary action of the natural barrier provided by the geological environment and the specific engineered barriers of the repository, as discussed in Section 2.3. The strategy for repository design is presented in the following section but, from the viewpoint of containment, a site needs to be selected with a geological environment which provides both conditions that allow the designed EBS to fulfil required safety functions and also has favourable features that limit migration of RNs (with a focus on groundwater release scenarios).

Thermal, hydraulic, mechanical and chemical (THMC[10]) conditions, including their potential evolution over time, will be characterised during investigation of the geological environment [21]. The conditions of the geological environment favourable to engineered barrier performance and/or restricting RN migration include:

- Lower temperatures at repository depth (e.g., ensuring buffer longevity).
- Slow groundwater flow (reducing solute transport rates).
- Sufficient mechanical strength (reducing deformation of tunnels).
- Favourable groundwater chemistry (reducing corrosion or waste degradation rates).

A repository is designed such that it sufficiently fulfils multi-barrier safety functions. If such a design is possible, even when considering various other design requirements and restrictions, a specification of a repository concept (or concepts) needs to be assessed to ensure that long-term safety will be provided.

For any repository design, the safety functions of the multi-barrier system should be verified by safety assessment (see Section 2.4). In addition, if necessary, the results of the safety assessment are fed back to the design of the repository, to iteratively improve specific safety functions. If it is shown that repository safety can be demonstrated, the site may be selected as a potential repository host and specification of a disposal system tailored to it developed. If more than one suitable site is found, several sites may go forward to the DI stage. The procedure for subsequent site selection is not further discussed in this document; the findings of the safety assessment will be a key, but not the only, input to such a selection decision.

2.2.3 Spatial scales during stepwise site selection

Chapter 1 presented the Nationwide Map (Figure 1.2-2), which identifies regions with preferred geological characteristics and also those suitable from the viewpoint of waste transport. This is a good starting point for NUMO’s site surveys, but these need to be systematically developed from a nationwide scale to regional comparisons. The regional databases also include material that is not more widely available, such as chemical properties deep underground, which could not be assessed in the map [34]. The stepwise assessment of all relevant geological conditions during the LS, PI and DI stages is shown in Figure 2.2-1, indicating how they are analysed in terms of repository construction and safety in order to determine the scientific suitability of sites.

[10] N.B. C also implicitly includes biological processes. N.B. This footnote is not included in the Japanese version of the report.

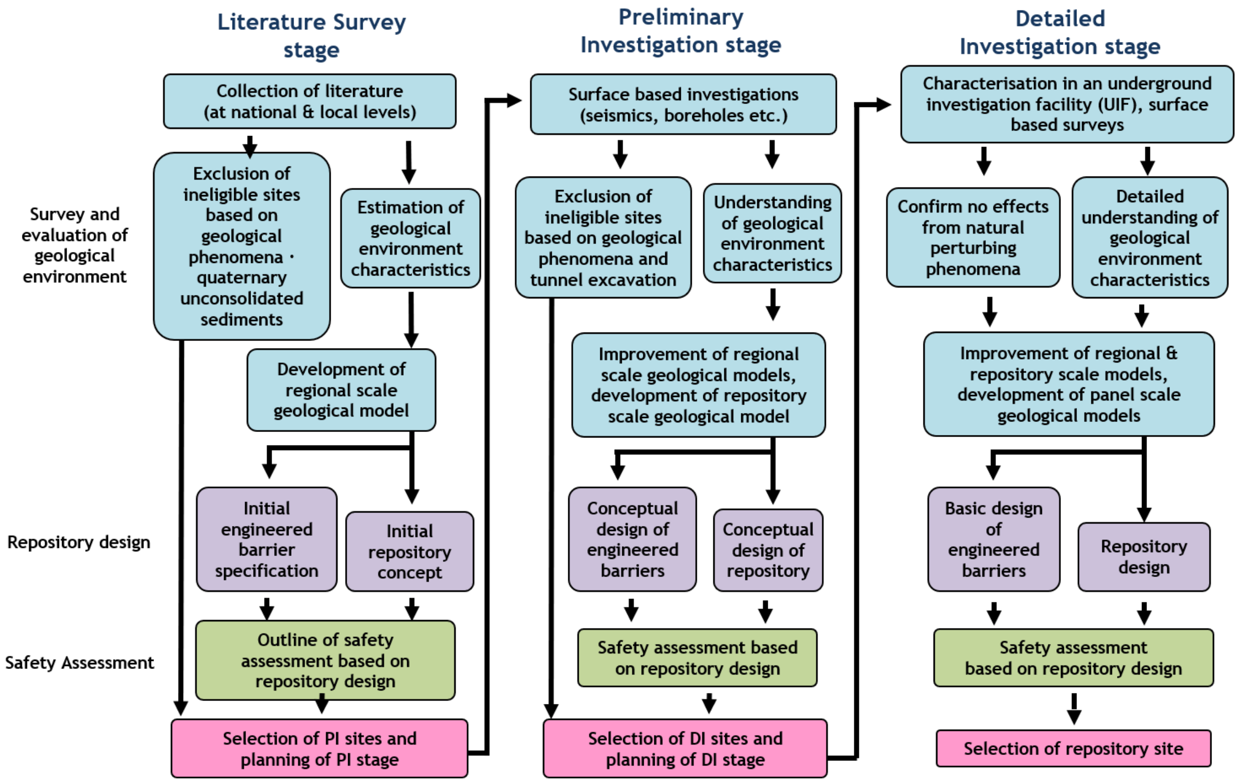

Figure 2.2-1 Stepwise characterisation of the geological environment, design of the repository and safety assessment
(Modified from Advisory Committee for Natural Resources and Energy, 2017 [34])

At the LS stage, the focus is on using information available on a nationwide scale to assess exclusion factors, such as distribution and activity of Quaternary volcanoes and active faults, extent of likely uplift and erosion, and presence or absence of natural resources. In addition, for non-excluded areas, the geological environment characteristics are synthesised in a three-dimensional site descriptive model[11] (3D SDM) which also schematically represents its expected long-term evolution.

At the PI stage, a series of geological investigations will be systematically implemented, targeting both the PIA and its surroundings [33]. Specifically, geophysical and borehole surveys will determine the local extent of the influence of Quaternary volcanoes, active faults, and uplift and erosion to confirm the LS assessment of eligibility. In addition, geological structures and characteristics of the deep environment will be determined to improve site understanding and evaluate its long-term evolution. This allows the 3D SDM to be refined, and a conceptual model for the long-term evolution of the geological environment to be developed ("4D SDM").

In the first half of the DI phase, more detailed information about the candidate host rock(s) is obtained by surface-based investigations, to further refine the 4D SDM. In the second half

[11] A SDM is a synthesis of geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry and the surface system, describing geological structures and various properties, considering past and on-going processes". However, the SDM has several different parts (e.g. geological structures, hydrogeological properties, thermal properties,…), that can be differently represented on different scales (with higher resolution in the more detailed scales), and aspects of the SDM could be represented by numerical simulation models (like a DFN groundwater flow and migration model for a part of the system). Still all these components need to be consistent (e.g. features of different hydraulic properties in the hydrogeological representation should reflect the geological features of the site).

of this phase, geological characterisation is extended by constructing an underground investigation facility (UIF) to confirm that the candidate host rock meets the legal requirements, and to obtain detailed information important for repository design and safety assessment, such as that related to RN migration and retardation. Based on the results of these investigations, repository designs and safety assessments are updated to support selection of a repository construction site.

Figure 2.2-2 schematically illustrates the scope of such three-phase site characterisation, narrowing in to the preferred repository location as it progresses from LS to PI to DI, while the level of detail increases. During all stages, the surface environment and other "non-geological" factors of importance for the site selection will also be characterised.

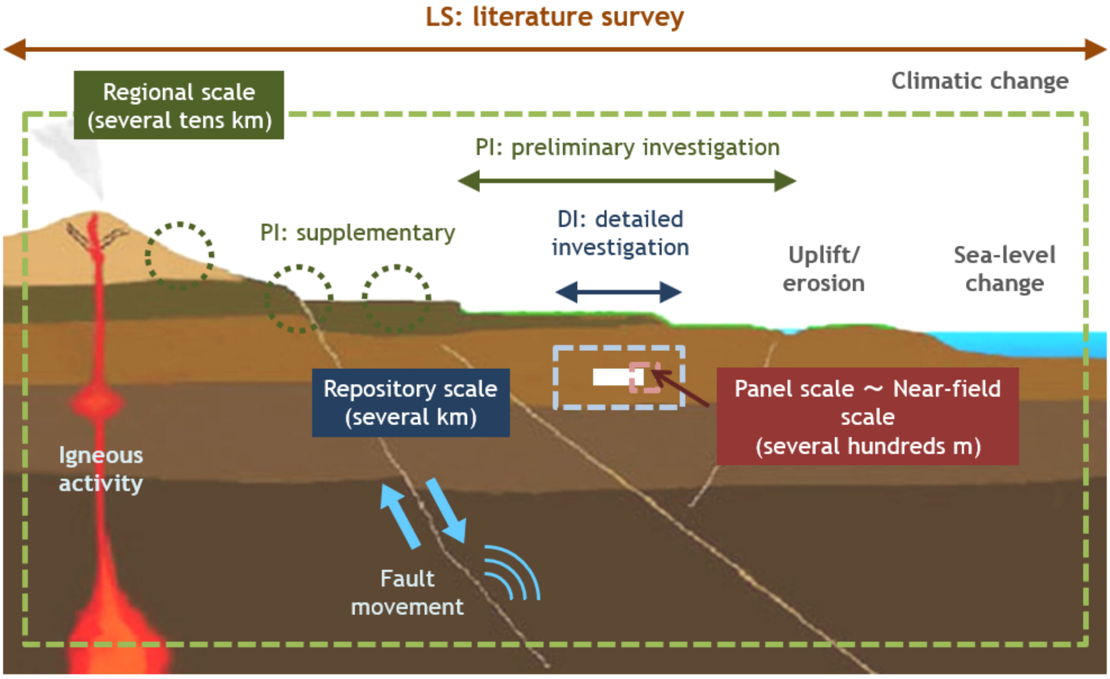

Figure 2.2-2 Three stages of site investigation and their relationship to site descriptive model scales (regional, repository and panel). Not illustrated in the figure is that regional studies (e.g., of tectonics and seismicity) may need to continue also in the DI stage.
(Modified from Advisory Committee for Natural Resources and Energy, 2017 [34])

2.2.4 Development of site descriptive models (SDMs)

NUMO has to integrate key properties of the geological environment into a representative model, incorporating attributes of a site that extend over large areas and depths and which are inherently heterogeneous on all scales. Characterisation needs to consider all relevant spatial scales, although the level of detail required is different, being greatest for the volume of rock containing the repository and, in particular, the most critical parts of the geological barrier from a safety assessment viewpoint. The key features of the geosphere and their spatial extent are site- and design-specific and are determined from the output of the associated safety assessment. These are captured in a site descriptive model (SDM), which is presented in the form of a series of nested representations on different scales and levels of detail.

From the viewpoint of the design of the repository, SDM representations on the following scales will be required (see Figure 2.2-2):

- Tens of km × tens of km around potential sites (regional scale), aimed at determining suitable isolation functions of potential repository locations in terms of natural hazards and the regional groundwater flow field.
- Several km × several km (repository scale), containing the entire potential repository footprint and all underground facilities, to assess constraints on the layout of emplacement zones.
- Several hundred metres × several hundred metres (panel scale), defining the near-field environment as required for design and configuration of engineered barriers and associated emplacement zones.

Meanwhile, from the safety assessment viewpoint, the following scales will be required:

- Tens of km × tens of km (regional scale) containing the potential site for identifying transport paths from the repository to the discharge point of RNs to the biosphere.
- Several km × several km (repository scale), for evaluating nuclide migration in the repository according to the layout of emplacement zones and the impact of repository-induced features such as the excavation damaged zone (EDZ).
- Several hundred metres × several hundred metres (panel scale), for evaluating nuclide release and migration depending on specifications of the EBS and the characteristics of the host rock immediately around the repository (near-field).

Thus, the SDM is developed on three spatial scales; regional scale (tens of km × tens of km), repository scale (several km × several km), panel and near-field scale (several hundred metres × several hundred metres). For the sake of completeness, it is noted that, for safety assessment, "micro-scale" models of flow paths are also required in order to quantify RN migration processes. These nested models are developed to ensure sufficient consistency of THMC conditions within and between them, with a level of detail of geological information and relevant processes and their couplings that is appropriate to the investigation phases considered, the technology availability, the features of analytical models and capabilities of calculation codes, etc.

As discussed in Section 3.2, the LS, PI and DI stages of site characterisation and evaluation are planned and implemented based on such a hierarchical model.

2.2.5 Approach adopted for site assessment and SDM construction

Prior to the availability of candidate sites, establishing the basis for demonstration of the capacity to model relevant geological environments at a level appropriate for site selection as discussed in Chapter 3 is based on:

- Systematic appraisal of the current state-of-the-art of the science and technology required for site suitability assessment in order to establish a basis for the approach adopted.
- Presentation of a concept for stepwise site characterisation along with demonstration of the technology for interpretation and integration of expected output to form the basis for design and safety assessment.
- Illustration of "representative host rock types", as preparation for the literature study, taking account of the requirements and standards of scientifically preferable and unpreferable areas [32] and utilising a compilation of geological information on a nationwide scale, with a focus on selecting areas that are potentially suitable among Japan's diverse geological environments.

- For each representative host rock type, constructing an illustrative SDM that includes all key features (e.g., major fault zones) that are required for realistically assessing its advantages and disadvantages in terms of repository design and safety assessment.

Construction of representative SDMs is based on the following considerations.

1. For the construction of the regional scale SDM, as indicated in Figure 2.2-2, surface topography and underlying geological structures are represented for a large enough area to capture all key factors influencing a repository – generally including an entire river catchment basin.

2. The SDM should take into account the long-term changes in topography and geological structure due to uplift and erosion and the associated changes in the characteristics of the deep environment. These processes are strongly dependent on site-specific conditions and, in this report, appropriate site selection as described in Sections 2.2.2 and 2.2.3 should ensure that the repository host rock considered is sufficiently deep to be unaffected by uplift and erosion, and that favourable geological characteristics will be maintained over a long period of time. The SDM is constructed for such a deep host rock, which is assumed to change slowly but have little impact on the design and safety assessment of the repository. In the assessment of safety after closure, the possible effects of uplift and erosion on the safety function of the host rock in the long term, relative to the depth considered in the design, would be considered (see Section 2.4.4).

3. In actual site selection, investigations are carried out at sites that do not clearly fail with respect to the exclusion criteria [32]. In this report, the SDM is constructed based on the geological environment information collected on a nationwide scale as described above, despite the fact that some of this information is obtained from the areas that would be excluded, such as in the vicinity of active faults, where significant uplift/erosion have occurred and where mineral resources exist. Although these areas are not acceptable, they were included in order to represent the characteristics of deep rocks that are widely distributed in Japan. Nevertheless, the SDM is developed excluding geological information from areas within a radius of 15 km of the centre of Quaternary volcanoes and areas with extensive depths of Quaternary sedimentary and volcanic rocks - which have clearly unfavourable characteristics for geological disposal (see Section 3.3.2).

At the panel scale (several hundred m × several hundred m), assessment of engineered barrier specifications and tunnel shapes/layouts requires a detailed model of the three-dimensional fracture distribution in the surrounding host rock. To provide the input for the calculational models used, a representation of the SDM of 100 m × 100 m × 100 m is specified. In this report, this is called the near-field scale” to distinguish it from the panel scale representation.

2.3 Repository design strategy

Repository design for a specific geological environment should assure safety (radiological and general occupational), during construction, operation and for a long period of time after closure, while minimising impacts on the surrounding environment.

2.3.1 Stepwise repository design approach

In a repository design, the specifications of the repository (engineered barriers, surface facilities, underground layout, etc.) are determined so that the safety functions of the repository are assured for the defined SDM. A particular focus is containment of RNs and restriction of their migration.

In addition to ensuring safety (radiological safety, general occupational safety), the design of the repository should also take into account environmental protection of the area around the facility. The engineered barriers, which play an important role in ensuring safety after closure, should be designed to be robust by assigning important safety functions to each of the system components and providing sufficient margins for these functions to allow for inherent uncertainties. In order to ensure the robustness of the repository, even if the expected safety functions of one barrier element are degraded, the complementary safety functions of other barriers will ensure sufficient safety.

The design of a repository takes into account various factors, such as safety and engineering feasibility, based on the increasing geological knowledge base obtained during site investigations, together with associated general developments of scientific knowledge and available technology. Design is also constrained by regulatory requirements for the repository, which will be refined as the project progresses. In addition to scientific and technological advances, it is recognised that the socio-political boundary conditions surrounding the disposal project may change. In designing a repository, the design should adapt to these changing conditions and be gradually optimised from an illustrative concept to a conceptual design and then to a detailed design, in line with the phased investigation, as shown in Figure 2.2-1. To enable the design of a repository to be flexible enough to take this into account, the following approach is taken [40] [41] [42]:

- Incorporating multiple requirements as design factors, so that the repository can be designed and optimised in a consistent manner.
- Repository design options will emphasise flexibility in terms of their ability to be tailored to the variety of geological environments expected and the progress of science and technology during the long implementation period.
- Designing a repository with detail appropriate to the level of understanding of the geological environment, which increases during stepwise narrowing down of the investigated area.

The term “design factors” denotes the features and capability that the repository design is required to have, e.g. long-term post-closure safety, operational safety, engineering feasibility, retrievability and economic efficiency [40]. This is further elaborated in Chapter 4.

Design options include layouts of the underground facilities and the emplacement zones, waste emplacement configurations (e.g. vertical, horizontal) and materials of the EBS components, such as the overpack and buffer (see Section 4.2.3). A HLW repository concept catalogue including examples of such design components has already been developed [41]. Such a range of design options facilitate tailoring to geological conditions better than conventional reference repository designs. Even technologies without demonstrated engineering feasibility at present can be considered, given expected future progress of science and technology over the period before the repository is licensed. Such a design concept is consistent with the aim of improving reliability of geological disposal based on Best Available Technology (BAT) [43].

2.3.2 Availability of engineering technology

In order to ensure implementation feasibility on the basis of technology currently available or under development, it is necessary to assess practicality of construction, operation and closure based on the specifications of particular designs.

For surface facilities, relevant technology is well established and experience has been gained in the construction, operation and waste transport of existing nuclear facilities, such as those for HLW interim storage, in Japan and abroad. For underground facilities, the knowledge base includes experience in the construction of other large-scale underground structures and testing of technology in domestic and international underground laboratories. This will be complemented by demonstration tests of technology related to construction, operation and closure in a UIF constructed at candidate sites in the second half of the detailed investigation phase. In addition to technology development, quality control checks prior to and during operation (e.g. pre-service inspections, regular facility inspections), together with demonstrations in the UIF, will provide the verification necessary to ensure safety of construction and operation.

2.3.3 Retrievability, environmental protection and monitoring considerations

As stated previously, disposal facilities should allow for reversibility and possible waste recovery during the stages of construction and operation, while assuring environmental protection that is confirmed by monitoring, as noted below.

(1) Assuring reversibility and retrievability

As described in Section 2.1.3 (2), the Basic Policy on Final Disposal specifies that the repository operator shall ensure project reversibility, to enable future generations to provide input on decisions on the implementation approach and respond to advances in science and technology. NUMO will also ensure practicality of waste retrieval during the period before repository closure, without compromising other safety requirements. Also as required by the Basic Policy on Final Disposal, research institutes will develop safe and technically practical methods to recover all designated radioactive wastes should this ever be required.

(2) Environmental protection

Studies of potential repository impacts on the atmosphere, water, soil, biodiversity, etc. will aim to introduce appropriate measures to reduce the burden on the environment (for example, reduce emissions of greenhouse gases). This will particularly consider the construction of the UIF in the second part of DI and subsequent repository construction, operation and closure and will capture experience in other major construction projects. In addition, recent laws and regulations related to the enforcement of environmental conservation will be fully reflected in the geological disposal implementation plan. For more details, see Supporting Report 2-6.

(3) Monitoring

In a geological disposal project, various types of monitoring are carried out from the initiation of site investigations to final closure to contribute to safety and environmental protection. Monitoring is an important means of confirming that the project is being carried out properly, and is essential for enhancing confidence in it. The closure of a repository is a prerequisite for achieving a passively safe condition that does not require active management, such as monitoring, from the point of view of safety. However, monitoring may continue as necessary, based on the needs of society and other stakeholders, for the period between closure and the end of any subsequent institutional control [18].

Monitoring objectives are classified into the following four categories [44], assuring:

- Radiological safety during operation.
- A suitable working environment during construction and operation.
- Environmental protection of the surroundings.
- Long-term safety after closure, by confirming the expected behaviour of the engineered barriers (for example, saturation of buffer material after backfilling) and surrounding host rock (for example, recovery of groundwater level).

Monitoring commences at the stage when field work is initiated, tailored to site properties (surface environment, social conditions of the region, geological setting) and associated repository design and construction/operation plans. The monitoring programme also takes into account the needs of the safety assessment to confirm or characterise specific phenomena and, if required, provide feedback to improve design and operational methods. Monitoring focuses on quantifying temporal changes in parameters and thus it is important to fully characterise the initial, undisturbed state (baseline) along with its inherent variability before invasive actions commence on site.

Monitoring technology for environmental protection is well established for similar major construction projects, while that for radiological safety can be taken from the long history of such work in the nuclear industry. Confirmation of post-closure safety is more challenging, and will possibly require modification of existing technology or development of new approaches - for further details, see Supporting Report 2-7.

2.3.4 Approach for the development of repository design

As the conditions of the geological environment cannot be specified in detail before candidate sites come forward, development of repository design is an iterative process and involves the following (described in more detail in Chapter 4):

- Demonstrating the availability of state-of-the-art design technology for establishing a safe repository with flexibility to respond to a variety of site conditions and social environments (systematic design requirements methodology, reference designs and design options).
- Starting from the H12 [20] and TRU-2 [12] reports, focusing technology development to target SDMs, illustrating repository design specifications that meet pre- and post-closure safety requirements and also demonstrate engineering feasibility for construction, operation and closure.
- Applying a methodology in which specific features of SDMs, such as major fault zones, are specifically assessed to determine their impacts – both positive and negative – on different disposal concepts.

- Assessing the specifications for illustrative repository designs to determine if implementation (including any required reversibility/retrievability) is practical, based on existing engineering technology or that reasonably expected to be developed in the future.
- Developing plans for environmental protection and monitoring, based initially on information about the surface environment and social conditions of the site accumulated during the LS phase. As this is very site-specific, it is not specifically discussed in this report.

2.4 Safety assessment strategy

Operational and post-closure safety will be assessed based on the information on selected sites and associated repository designs and available scientific and technological knowledge, in the light of relevant regulatory standards and the requirements of stakeholders.

2.4.1 Operational safety assessment

The objective of the operational safety assessment is to confirm, on the basis of regulatory standards to be developed, that the safety of the workers and local residents around the repository is ensured during the construction of the repository (surface and underground facilities), handling operations such as waste transport, acceptance/inspection/encapsulation, waste emplacement and closure. It should be noted that disaster prevention and industrial safety measures against perturbations without radiological impacts will be addressed by conventional risk management throughout the periods of construction, operation and closure of the repository.

The safety of disposal facilities is generally assessed, as in other facilities that handle radioactive waste, based on regulations contained in the Nuclear Reactors Regulation Act. However, it is noted that the mining operations involved in constructing and operating the repository may involve hazards not usually considered for nuclear facilities. Since the accident at the Fukushima Daiichi Nuclear Power Plant, new regulations aimed at reviewing the design of reactors and other nuclear facilities have been formulated. This has resulted in new regulations for HLW management facilities, enacted as “Rules Concerning the Criteria of Location, Structure and System of the Waste Management Facility” (hereafter the “Programme Licensing Rules”). The Programme Licensing Rules require not only designing a repository that ensures normal safety requirements, such as shielding and containment, but also demonstrating that it has taken into consideration major perturbations, such as earthquakes, tsunamis and other external impacts (other natural hazards, anthropogenic hazards such as plane crashes), when defining the location of the repository and designing appropriate counter-measures. It also requires installing measures to protect against illegal access or introduction of hazardous materials such as explosives into the repository. In the evaluation of a maximum design-basis accident, it is required to evaluate the likelihood that the local residents around the repository site could be exposed to radiation by accidents, such as dropping of waste packages, in spite of the various safety counter-measures implemented.

The IAEA [45] has also published a guide on safety case development and safety assessment for radioactive waste conditioning and storage facilities and their operations. In this guide, the approach to the safety assessment is based on the analysis of the design and operation of the facility, the establishment of a series of scenarios of conditions and events that may lead to radiation exposure of humans and contamination of the surrounding environment during operation, and the development of a safety case based on these scenarios. Based on the set of scenarios, the radiological effects on humans and the surrounding environment are to be analytically assessed and the results of these analyses are to be compared with radiation protection standards to confirm that the repository and the operating method are designed to ensure sufficient safety.

NUMO will develop technologies to identify events that may affect radiological safety before repository closure, to establish safety assessment scenarios, and to develop models and data sets for analysis and assessment, taking into account these international guidelines and relevant future safety regulations. Based on this, NUMO will identify appropriate measures to mitigate these risks and incorporate these into the repository design.

2.4.2 Approach for operational safety assessment

At present, criteria for geological disposal facilities have not been formulated within the Programme Licensing Rules. Further, in the absence of a specific repository site, the extent to which the relevant surface environmental conditions can be defined is very limited. This, in turn, constrains sensible evaluation of the impact of site-specific external perturbations, such as earthquakes or tsunamis. In addition, with regard to prevention of illegal entry into the repository, as implementation will occur only in the future the emphasis is on monitoring developments in setting standards for geological disposal facilities and relevant measures implemented in other nuclear facilities. Nevertheless, evaluation of safety is possible for maximum design basis accidents.

Therefore, as described in detail in Chapter 5, this report will:

- Illustrate the concepts and methodology of radiological safety assessment for operational processes on both workers and local residents with reference to the safety regulations for other relevant nuclear facilities.
- Present results of the illustrative operational safety assessments for specified disposal concepts, while assessing the practicality of potential counter-measures to reduce associated risks.

2.4.3 Post-closure safety assessment

NUMO’s evaluation of long-term post-closure safety adopts methodology compatible with that used internationally. For repository designs tailored to geological environments at selected sites, such assessments will define representative scenarios to evaluate the radiological impact on the surrounding populace, with consideration of uncertainties involved. Such analysis should confirm that the repository meets safety standards over the assessment period and will not have a significant impact on the biosphere.

Safety assessments are not intended to predict future repository evolution or the associated human exposure to radioactivity, but rather to comprehensively assess whether the required isolation and containment of radioactive waste can be achieved. Inherently, such safety functions will gradually degrade with time and eventually be lost, but representative credible future evolutions (scenarios) can be defined that capture current scientific knowledge along with associated uncertainties.

Such scenarios allow potential future release and migration of RNs to be quantified although, due to particularly large uncertainties in the future surface environment and human lifestyles, idealised biosphere representations need to be used to convert radioactivity releases into possible radiological impacts. Numerical values of calculated doses need to be used with great care, but can serve as indicators of expected repository performance, which can be complemented by other supplementary indicators and arguments.

In accordance with the aim of safety assessment, it is important to consider all possible conditions that may occur in a repository, but focus on likely conditions that are important for determining the safety of the repository. For this purpose, a "FEP" catalogue is used, which describes the characteristics of each element of the repository that may be relevant to its safety function (Feature), the events that affect these characteristics (Event), and the process of the repository's evolution over time (Process). In order to estimate resulting dose, mathematical models and data sets are used to describe the release and migration of RNs from through the EBS and host rock, and into the biosphere. The future human exposure to RNs migrating into the biosphere depends on the transport of RNs depending on surface conditions (topography, land use, etc.) and the mode of exposure as a result of human lifestyles (sources of drinking water, extent of consumption of local crops and livestock, etc.).

NUMO has been working on technology development related to fundamental components of the safety assessment: scenario development, modelling and preparation of required data sets [18]. Additionally, for the PI stage of site characterisation, a preliminary safety assessment manual that systematically outlines required procedures and methods has been produced [46]. With a view to subsequent site selection, extension and refinement of this safety assessment methodology and confirmation of its applicability for specific sites will be necessary.

Preparation of an appropriate safety assessment analysis toolkit is especially important to allow objective evaluation and comparison of the performance of alternative disposal concepts, where the methodology must also handle different uncertainties in terms of site conditions and repository specifications.

2.4.4 Approach adopted for post-closure safety assessment

The regulatory framework for safety assessment in Japan will be developed in the future and thus, in this report, guidelines on safety standards and indicators indicated by international organisations (e.g. IAEA Safety Standards Series [17] [19] [43] and ICRP recommendations [47] [48]) and safety regulations in other countries with similar projects are used to provide reference performance targets for future human exposure.

In recent years, the need for radiation protection of both the environment and non-human organisms has been discussed (e.g. ICRP recommendations [49]). In addition, non-radioactive hazardous substances contained in the waste could have post-closure impacts on humans and the environment. Such issues are not considered in this report, but will be addressed in the future.

For the scenario framework, a risk-informed approach that combines the disaggregated likelihood of occurrence and the significance of the consequence of the scenario has become popular among international organisations and regulatory bodies since 2000 (see Section 6.1.5(1)). While the scenarios leading to radiation exposure via groundwater flow are the main focus of the assessment, scenarios that include events that lead to the loss of the isolation functions or a significant reduction of the containment function are developed as these may need to be considered for specific sites.

The safety evaluation period can be determined by consideration of the following points in general, referring to IAEA [43], OECD/NEA [31] and the safety regulations in relevant countries:

- The time of the maximum estimated dose to the general public.
- The time at which the potential hazards of radioactive waste have decayed to a negligible level.
- The time at which uncertainty of evaluation becomes too large for models to be meaningful.
- The time required to assess impacts of slow processes and occurrence of extremely rare events.
- Timescales of stakeholder concerns.

In some countries, the period for quantitative assessment, taking into account the above aspects, is specifically indicated in safety regulations and, in many cases, a time frame of 1 My is adopted (e.g. [50] [51] [52]). In Japan, the safety evaluation period for geological disposal is under discussion and will be specified in future regulatory standards. Therefore, in this report, the safety evaluation period is not selected on a scientific basis, but is taken to be long enough that it will cover the maximum impact from credible groundwater release scenarios.

Based on the above, post-closure safety assessment, as discussed in more detail in Chapter 6, includes the following:

- A risk-informed approach, introduced in order to appropriately deal with various kinds of uncertainties. The focus is on an appropriate concept and methodology to qualitatively assess safety on the basis of international guidelines and other considerations.
- A safety assessment analysis method is developed in order to allow the objective evaluation and comparison of performance of different geological environments and associated repository designs.
- Post-closure long-term safety assessments for the SDMs developed in Chapter 3 and the repository designs tailored to them in Chapter 4, considering the likelihood of relevant scenarios describing their future evolution. Results are discussed in the light of tentative performance targets, accepting current limitations on available knowledge and hence the models and databases used.
- By appropriate site selection, it is assumed that the host rock is little affected by uplift and erosion, and that favourable geological characteristics will be maintained for a sufficiently long time (see Section 2.2.5). However, to ensure this, the potential effects of long-term uplift and erosion on the safety functions of the host rock are considered (see Supporting Report 6-10).
- Matters that depend on the site-specific geological environment and construction and operating methods, such as the degree of disturbance of conditions during construction and operation of the repository and the process of their recovery, are presented as issues to be considered after site identification, unless they could be conservatively disregarded in the safety assessment.

2.5 Management systems

Responding to the challenges faced when developing a safety strategy under the requirements described above is facilitated by appropriate management tools and methodology. These integrate all the actions carried out and ensure consistency in the repository concepts developed for a variety of geological environments, with respect to construction, operational and post-closure safety, feasibility, economic efficiency, and social acceptance requirements, whilst also considering trade-offs among them.

A geological disposal programme continues for a long period of time and needs to be flexible so that it can respond not only to progress in technology but also to changes in societal boundary conditions. This has been discussed at a conceptual level in the “NUMO structured approach” [53] and in the 2010 report [18]. The key components of the strategy for ensuring safety while maintaining flexibility can be summarised as follows:

- Development of management methodologies for close coupling of the geological investigations and site evaluation, repository design and safety assessment work, facilitating good communication between the staff involved in each field (Figure 2.5-1). This coupling will evolve naturally as the programme progresses, from site selection and the subsequent licensing phases, through construction, operation and closure.
- Comprehensive assessment of conventional and radiological risks to both workers and the general public at all programme stages. Setting and analysing appropriate scenarios allows identification of potential hazards from both normal and perturbed operations. Counter-measures are thus identified that could be implemented wherever required.
- Regular reviews to ensure that technology is maintained at state-of-the-art levels, reflecting developments in system understanding and advances in science. Any technical work performed by NUMO, including site selection and technology development, is subject to regular checks and review by external experts.
- Re-evaluation and updating of the safety case, including major decisions made based on it, in each phase of the programme. This is conducted to check that current regulatory guidelines and standards are complied with and also to provide continuous reassurance to the general public. Technical issues are also identified that should be reflected in subsequent updates of the safety case.

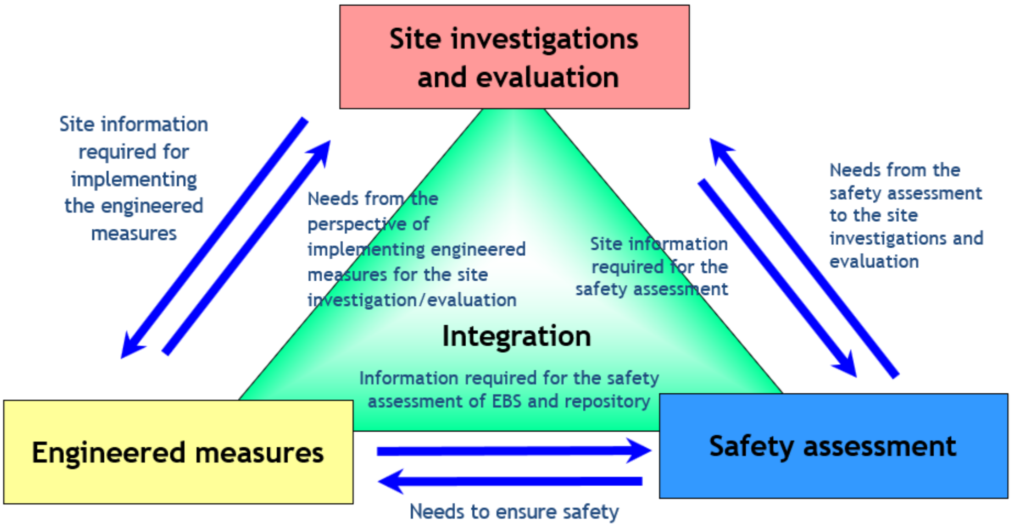

Figure 2.5-1 Coupling of site characterisation, repository design and safety assessment (based on Figure 4.2 in the 2010 report [18])

The design of the repository should be based on this information and incorporate sufficient safety margins. The safety assessment should confirm that radioactive material in the repository will not have a significant effect on humans, taking into account the various uncertainties inherent in the SDMs and in the repository designs. If it is judged that the required level of safety is not met, or if the uncertainty in the results of the assessment is so great that confidence in the results needs to be improved, the design and safety assessment of the repository should be re-examined, for example by expanding the geological information available to reduce the uncertainty.

If information is added or revised during the course of these activities, it is necessary to understand the extent to which this affects the investigation and assessment of the site, the design of the repository and the safety assessment and the integrated safety case. In order to achieve this, it is important for NUMO to have the overview required to lead integration of results and determine the direction of the work, as well as to ensure close communication between project managers in different disciplines, so that changed information and data can be passed between them and the decisions made reflect the consensus of all involved.

Coordination between technical disciplines, preliminary assessment of conventional and radiological risks and the preparation of response measures, repeated review of geological disposal technology, and the development of safety cases are all essential management tasks for ensuring safety. At the same time, the following issues should be addressed:

- How to deal with changes in the social environment and uncertainties in safety over the long term after repository closure.
- How to ensure the quality of all technical studies.
- How to share the vast amount of accumulated knowledge, information and data within and between generations.
- How to promote continuous technical development.
- How to ensure the availability of human resources in a variety of technical fields.

2.5.1 Uncertainty management

As already mentioned, the handling of uncertainty is extremely important, particularly because geological disposal involves unusually long timescales, both in terms of the duration of the project and in terms of ensuring safety after closure, and because the geological environment has inherently heterogeneous characteristics on all spatial scales.

The four basic approaches to dealing with uncertainty in geological disposal have been termed “identification”, “avoidance”, “reduction” and “assessment” [54]. Uncertainties are “identified” and “avoided” or “reduced” in the safety case developed at each stage of the project. For example, uncertainties in properties or events that are difficult to understand or predict, such as the distribution of geological characteristics over large spatial scales or the predicted evolution of a future geological disposal system over time, can be addressed by designing a robust repository that assures sufficient safety despite such uncertainties as determined by realistic and/or conservative assessments. Uncertainty should also be “reduced” by continual extension and improvement of the technical and scientific knowledge base. Nevertheless, uncertainty cannot be completely eliminated, so it is necessary to “assess” remaining uncertainty and decide whether it is acceptable while ensuring the safety of the repository. In staged site selection, uncertainty is quantified and reduced by refining the geological knowledge base as captured in SDMs, tailoring design of the repository to them and specifying the engineering techniques for implementation, while the remaining uncertainty is taken into account in the safety assessment, introducing conservatisms when required (see Supporting Report 2-8 for details).

In general, uncertainty is defined as aleatory uncertainty, due to inherent differences or variations in observed values of the system considered, and epistemic uncertainty, due to lack of knowledge or information about it [55]. In the site investigations, for example, in addition to aleatory uncertainty due to the inherent temporal and spatial heterogeneity of the geological environment, there is epistemic uncertainty involved in its conceptualisation within SDMs due to uncertainty in data (e.g. caused by measurement errors) and its resulting interpretation.

Over relevant spatial scales in the order of several kilometres and timescales of hundreds of thousands of years or more, it is clearly impossible to obtain enough observations to fully quantify all uncertainties [54]. Nevertheless, quantification of the heterogeneity of geological characteristics is carried out to the extent practicable (e.g., statistical analysis to define means, variances and standard deviations of data). In the case of important geological structures and natural events/processes that impact repository implementation and post-closure safety, the types, causes and degrees of uncertainty and the factors associated with these (e.g., the network structure of faults and fractures) are identified and responded to through the knowledge communication as shown in Figure 2.5-1.

In the design of a repository, the specifications of engineered barriers and underground facilities will be set in such a way that the required functions can be assured even if uncertainties in the site geology and in the analytical models and parameters used in the design process are taken into account. In addition, the quality of fabrication and its variability will be assessed through demonstration tests (e.g., mock-up tests, large-scale tests in URLs, etc.), and associated quality assurance protocols defined to ensure that as-built repository components meet specified requirements.

Uncertainties in safety assessment are often categorised and treated as being associated with scenarios, models and data. Scenarios are developed for credible evolutions of the disposal system, based on information integrated into the SDMs and associated repository design, taking into account uncertainties arising from lack of understanding or knowledge of phenomena and processes. Specifically, scenarios are classified into those that are likely to occur based on best current understanding, those that take into account uncertainties that can be reasonably established based on current scientific knowledge, and those that consider events with a low probability of occurrence. In this way, some impacts of uncertainty on the safety of a geological disposal system are taken into account.

As a starting point, the FEP catalogue is expanded based on the latest domestic and international knowledge and, to the extent possible, realistic scenarios should be derived from this. If realism is not practical, scenarios should be sufficiently conservative, utilising expert opinions on their appropriateness and completeness, if required. In this way, the risks of overlooking safety-critical scenarios or developing inappropriate scenario descriptions can be reduced.

In addition, since it is inherently impossible to predict human activities in the distant future (as noted in Section 2.4.3), or even assess any uncertainties involved, the biosphere assessment approach is based on internationally accepted concepts of stylised scenarios (e.g., IAEA (2012) [43], ICRP (2013) [48]). Stylised scenarios based on current human activities are also developed for potential future perturbations (human intrusion scenario).

Key uncertainties in the safety assessment models and associated databases for radiological consequence analysis of defined scenarios should be compensated for by including sufficient conservatism. For example, if it is difficult to establish sufficiently reliable models/databases, analyses should be carried out in such a way that conservative results can be obtained, e.g. by ignoring some of the expected positive functions of barriers or by using models and data that clearly give pessimistic results despite these uncertainties.

Important uncertainties are identified in the safety case developed at each siting stage and reflected in the investigation and technology development plan for the next stage. This step-by-step approach to uncertainty reduction ensures that the repository is constructed in a safe manner. Prior to the closure of the repository, periodic safety reviews, as stipulated in the Nuclear Reactor Regulation Act, will be carried out to capture the latest knowledge and the results of monitoring, thus reducing uncertainties associated with operational optimisation and post-closure safety.

During the 100-year lifetime of the project, there may be changes in socio-political and economic boundary conditions that affect its implementation. In the light of such uncertainties, a range of technical options will be developed (e.g., various disposal concept options) to allow for flexibility in responding to changes and minimise associated management risks for NUMO.

In general, the variability of geological characteristics is site-specific, while uncertainties about the quality of engineered barrier systems depend on the materials and manufacturing methods involved. Therefore, in this report, representative characteristics of the host rock are set by assessing nationwide literature, and uncertainties are generally not directly captured in the SDMs (exceptions involve groundwater chemistry, which plays an important role in performance of both engineered and natural barriers). Clearly, this is a limitation that would be addressed in updates to the SDMs. Similarly, for the physical properties of engineered barrier materials, representative values are set based on reported experimental data and uncertainties in these properties are currently not considered, but will be in the future. A summary of the treatment of the uncertainties in this report is given in Section 7.3.2.

2.5.2 Quality management (QM)

Quality management plays a very important role in both developing a safe repository and in the production of a report like the present one, which integrates the key components involved [56]. NUMO has developed a quality management system (QMS), which builds on ISO 9001 in order to manage the site investigations (LS, PI and DI), repository design and associated safety assessments together with the development of technology required to systematically implement a repository (construction, operation, and closure). In the NUMO QMS, procedures to ensure quality of repository implementation include:

- Quality goals and requirements for repository implementation and associated technical documents.
- Processes to check that such goals and requirements are met, including quality audits, monitoring and verification activities.
- Assurance of availability of required infrastructure and human resources to meet quality levels.
- Comprehensive production of records and long-term archiving of these.
- Correction of any non-conformity and associated preventative actions to prevent recurrence.

To ensure safety of repositories, technical quality management has to be tailored to key activities. For example, in preparation for geological investigation and evaluation of potential sites, NUMO has already produced a site investigation planning manual and a quality control (QC) guide for activities up to the stage of initiation of preliminary investigations [57]. This specifies a system in which the quality of the geological investigation methodology and procedures, as well as the primary data and synthesised output, are reviewed by both NUMO internal and external experts. In addition, a geological information management support system has been developed to assist in ensuring that databases produced are traceable and complete. Similar procedures and methods for the design of a repository and safety assessment have been compiled as guidebooks, to allow teams working under different site conditions or on facilities with different designs and safety assessments to achieve the same quality level.

The repository and components of the EBS are assured to meet the quality of design specifications by appropriate testing and inspection procedures, extended to the extent possible to include input information on geological environments, characteristics of waste packages, etc. The quality of the waste material will be assured by setting criteria for its acceptance in accordance with the approach described in Supporting Report 2-5. Specifically for repository design, a focus at the current stage is on verification that available technology can construct the engineered barriers to required quality levels, given the constraints of operational logistics (e.g. expected waste emplacement rate) and the challenges of working underground, predominantly using remote handling/tele-operated systems. This includes developing monitoring systems, to directly confirm the quality of the resultant EBS, and testing procedures to respond to any cases where required quality is not met.

Inherently, however, the quality of the EBS performance after closure cannot be directly verified and is dependent on the safety assessment analysis – and hence on the quality of approaches, models and databases used to implement this on the basis of the SDM and a representative range of future evolution scenarios. Individual system models and databases can be subject to expert review, to check quality of fundamental assumptions, and verified by inter-calibration with alternative models and formal methods of code testing. However, validation is limited to short-term tests, using laboratory or in-situ experiments, or more uncertain natural analogues. For more details of quality assurance (QA) of analytical codes and databases used in this report, see Supporting Report 2-9.

During the three phases of site characterisation, enormous volumes of data will be produced and the design and safety assessment analysis will be frequently updated. Updating, change management and communication of the huge multi-disciplinary knowledge base linking site investigation, design and safety – including the management of tacit knowledge accumulated by key staff – is recognised to be an important challenge and is a focus for systematic QMS and knowledge management system (KMS) development (see also Section 2.5.4).

The quality assurance of the results of technology development is important in order to develop a safety case based on BAT and the quality of technology development is promoted by a programme of obtaining technical reviews and advice from experts in all appropriate fields. Appropriate QA is also required when incorporating R&D results from other organisations into the geological disposal programme. Thus, NUMO employs established methodology to achieve the necessary quality of technical work. This includes production of scientific papers for peer-reviewed publications and technology development reports, which are reviewed by third parties.

The quality management framework described above has been applied to the establishment of the SDMs, design and safety assessment of the repository in this report. In addition, the system shown in Figure 1.4-4 in Section 1.4.2 ensures that the process and results of studies in this report are reviewed by experts to ensure the quality of the safety case. As described in Section 1.4.2, this report has been improved based on the review comments [58] from the "Special Review Committee on the NUMO Safety Case" of the Atomic Energy Society of Japan on the NUMO Safety Case Report (Review Version) (published in November 2018).

2.5.3 Requirements management

The implementation of a geological disposal programme requires the hierarchical consideration of a wide variety of requirements. These include technical requirements for ensuring the safety of a repository and requirements for quality management as mentioned above, as well as requirements from laws, regulations and policies defined by the national government, regulatory bodies, or requested by various stakeholders. In order to manage this, NUMO has developed a Requirements Management System (RMS) [59], aimed at systematically identifying the wide variety of requirements and managing them in an effective and transparent manner.

Such requirements and associated decisions need to be consistent in each phase of the programme, and also throughout the diverse range of technical work carried out by NUMO managers and technical teams. The RMS ensures completeness of the requirements and provides a mechanism for change management, with transparency and traceability, as requirements evolve with time associated with the stepwise progress of the programme, impacting decisions made based on these requirements (e.g. design specifications). This is complemented by structured management of associated knowledge (see Section 2.5.4), allowing appropriate responses for any case where significant changes in boundary conditions occur, with reference to the basis of the recorded background to past decisions or judgments.

The current requirements for the characterisation of geological environments, repository design and safety assessment were re-examined during the compilation of this report. This information will be recorded as necessary in an expanded and updated RMS. As further discussed in Chapter 7, development of the RMS will be essential, but also complex since it will involve interaction between all the technical areas and groups working to implement NUMO's programme.

2.5.4 Knowledge management

The Japanese geological disposal programme will develop over a long period of time, extending over a century or more, comprising site characterisation, design, construction, operation and closure of the repository, including the preceding R&D period. The vast amount of knowledge, information and data produced inside and outside Japan at each step of the programme needs to be compiled systematically and also transferred to future generations. Knowledge, information and data can be defined as follows, referring to the OECD/NEA study [60]:

- Knowledge: know-how, understanding, experience, insight, grounded intuition and contextualised information.
- Information: contextualised, categorised, calculated and condensed data.
- Data: facts and figures related to specific topics, but not organised in any way.

Management of knowledge, information and data (hereafter collectively termed knowledge) includes, as mentioned in the QM section (Section 2.5.2), procedures to process information and data reliably in multi-disciplinary, coordinated work, including site investigation, design and safety assessment. It also needs management of knowledge and information used as a basis for various decisions in each project phase, as described in the requirements management section (Section 2.5.3). Recognising this, a KMS is under development, which securely integrates, synthesises and archives the knowledge base, while ensuring transparency, traceability and retrievability.

Given that the knowledge forming the basis for geological disposal has been increasing exponentially with time, there are clear limitations in the traditional "report-based" knowledge management systems. This was recognised by JAEA [61], which led to the development of an advanced KMS which can be linked to associated quality and requirements management systems [61] [62]. A web-based communication platform, CoolRep [63], was also developed. The JAEA KMS has been refined further, with the intention of integrating it into the NUMO RMS described above, reflecting the role of JAEA as an independent R&D organisation providing both NUMO and regulatory agencies with fundamental scientific and technical knowledge. As the concept for the development of the JAEA KMS is based on the structure of a safety case, it is well suited to systematically managing, quality assuring, communicating and archiving knowledge accumulated during the compilation of this report and presenting it to all stakeholders.

The safety case is developed based on integration of technical knowledge and information from a wide range of fields of expertise. For this reason, it is not easy to overview the entire safety case, even for experts in the specific fields included. Therefore, special communication efforts will be required for the explanation of the safety arguments included at different levels, responding to needs of different audiences, ranging from experts in different scientific fields to non-technical stakeholders.

In order to promote such safety communication, several documents with different content tailored to the knowledge level of readers, as well as a web-based communication platform (related to CoolRep mentioned above), will be produced. These increase the opportunities for users to access and easily view the knowledge and information that they are interested in, at a level defined by hierarchical electronic documents, as indicated in Figure 1.3-2. In the future, such material on the safety case will be available via the NUMO website.

2.5.5 Management of scientific and technology development

To support implementation of geological disposal, NUMO and related research institutions collaborate in strategic technical development and periodic evaluation of progress, as required by the Basic Policy on Final Disposal. This interaction between NUMO and research institutions is facilitated by meetings of the Coordination Council on Basic R&D of Geological Disposal (hereafter referred to as the "Coordination Council"), established by METI in 2005, which link R&D programmes [64] [65] to NUMO's technical development plan and are updated to respond to changes in it. This Coordination Council was later reorganised to also consider the practical R&D needed for implementation in addition to more fundamental R&D [66]. This will promote the development of technology needed to safely implement geological disposal in an economic and efficient manner.

NUMO already has a structured programme for developing and testing the technology that will be required for the LS and initial PI stages, as outlined in the medium-term R&D plan [67] implemented by NUMO over the five fiscal years from 2013 to 2017. However, this programme will need to be adapted to the findings obtained as the siting programme progresses, as discussed in Section 7.4 of this report.

The technical issues identified in this report (see following chapters), as well as the issues identified from the results of the technical development and fundamental R&D, were reflected in the general research and development plan for geological disposal (Fiscal Years 2018-2022) [68], which was compiled on the basis of the Coordination Council. In line with this overall plan, NUMO has developed a mid-term technical development plan covering the period from FY2018 to FY2022 [69].

NUMO will continue to develop geological disposal technology and, after a site is identified, the necessary technology will be implemented in a timely and phased manner according to the characteristics of the site, reflecting the latest scientific knowledge (see Section 7.4 of this report for further details). The management of the project will be facilitated by a technology development plan, which is formulated by repeatedly summarising the safety cases at appropriate times to clarify the technical issues to be addressed in the future. In this process, a PDCA (Plan-Do-Check-Act) cycle[12] is applied at various levels to promote constant improvement and upgrading of the geological disposal technology.

2.5.6 Management of human resources

Geological disposal involves a complex programme that includes many disciplines. The personnel required are highly qualified staff, including both experts in each relevant field of expertise and experienced generalists who can conduct cross-cutting overviews of the output from all included disciplines. Recruiting and training the required human resources and instilling in them an appropriate working culture for an implementing body is a key component of both quality and knowledge management, as described above, and is facilitated by the toolkits developed in these areas. Planning and implementation of technology

[12] The PDCA cycle is a management method in which the business processes are continuously improved by repeatedly performing four fundamental activities: planning (plan) → execution (do) → evaluation (check) → improvement (act).

development is inherently constrained by the available manpower – both in NUMO and in relevant R&D organisations – and hence the management of human resources is thus recognised as being extremely important and explicitly included in the R&D plan [69]. As a part of this plan, NUMO has established training courses to develop young personnel in collaboration with relevant organisations in Japan [70].

In addition to domestic resources in Japan, it will be important to encourage the participation of external human resources from the international community. Especially when ensuring technical reliability, the participation of an international network is essential in, for example, the preparation of qualified English documents and review of the safety case to ensure that it meets international standards.

Together with the utilisation of tools for quality, requirements and knowledge management as described above, NUMO will formally manage human resources, for example, when planning systematic recruiting and training, as well as in cooperation with relevant organisations inside and outside Japan through:

- Recruitment of both new graduates from universities and experienced workers in the field of geological disposal, based on the programme schedule and required expertise identified in the implementation plan. This will be coupled to cooperation in maintenance of the key infrastructure (e.g. URLs) and knowledge transfer from relevant R&D organisations by long-term attachment of staff and collaboration in joint research projects.
- Improvement of tacit knowledge and practical abilities through staff attachment to, or participation in, cooperative programmes between NUMO and other implementing/R&D organisations involved in radioactive waste disposal, both inside and outside Japan.
- Ensuring that NUMO’s technological capabilities and tacit knowledge base are maintained, improved and passed to future generations of staff through the periodic development of safety cases and participation in joint research projects.
- Assessment and introduction of programmes to foster human resources with a wide range of multi-disciplinary knowledge and project management skills (generalists).

In the compilation of this report, next-generation human resources were cultivated through collaboration of younger staff with relevant research institutions, discussions with external experts, participation in documentation of the project, and participation in the review process inside and outside Japan.

2.6 Summary

In this chapter, based on the current status of Japan's geological disposal programme, the basic implementation policy to ensure effective site selection, design of the repository and associated safety assessment has been outlined. In addition, the approach to development of the safety case described in this report has also been outlined, highlighting boundary conditions and constraints at the present pre-siting stage.

In Chapters 3 to 6 of this report, the specific approaches to the selection and modelling of geological environments suitable for geological disposal, repository design and engineering technology, and the assessment of operational and post-closure long-term safety are set out. In each of these areas, application of the uncertainty, quality and knowledge management approaches described in Section 2.5 of this Chapter is included. Chapter 7 summarises these results and discusses integration of these as a safety case.

Supporting Reports (SRs)

SR 2-1 Definition of specified waste for geological disposal
SR 2-2 Characteristics and quantity of waste (HLW)
SR 2-3 Waste inventory for design and safety assessment
SR 2-4 Characteristics and quantity of waste (TRU)
SR 2-5 The concept of waste acceptance criteria
SR 2-6 The approach to environmental conservation
SR 2-7 The concept for monitoring
SR 2-8 Managing uncertainty
SR 2-9 Assessment of the reliability of numerical analyses

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3 SELECTION AND MODELLING OF GEOLOGICAL ENVIRONMENTS SUITABLE FOR GEOLOGICAL DISPOSAL

Based on the fundamental strategy for site selection described in Section 2.2, this chapter is compiled for the following purposes:

- To demonstrate that the concept for site suitability assessment and associated investigation and evaluation methods have been developed systematically, based on the latest scientific knowledge and technological developments relevant to Japan's geological environment.
- To demonstrate the technology for interpreting and integrating information on the geological environment, synthesising this in a stepwise manner into a model of the host rock in its geological setting, which is the basis for the design and safety assessment of the repository.

In Section 3.1, in addition to the relevant safety features expected for the geological environment, the basic approach to addressing the factors that can affect these safety features is described. Additionally, an overview of the geological characteristics widely observed in deep environments in Japan is given, which shows that those with the required safety functions can be selected.

In Section 3.2, based on the basic concept for site selection described in Chapter 2, an approach is presented for excluding geological environments with significant effects of natural phenomena that could impair the safety features, such as volcanoes/igneous activity, earthquake/fault activity, and significant uplift/erosion. This allows focusing on those which maintain favourable characteristics for a sufficiently long period of time. Required investigation and evaluation methods for such a selection process are also summarised.

Section 3.3 outlines how, for potentially suitable host rocks that might result from site selection (and for which the safety functions are expected to remain intact for a long time), to construct and show the applicability of a Site Descriptive Model (SDM). The SDM is derived by interpreting and integrating information on the geological environment on the spatial scales required for the design and safety assessment of the repository described in Chapter 2. This model provides an important basis for efforts related to repository design and engineering (described in Chapter 4) and evaluation of long-term, post-closure safety (described in Chapter 6).

Section 3.4 describes the scientific knowledge that serves as the basis for examining rare perturbing event scenarios for the evaluation of post-closure safety, with emphasis on the probability of occurrence of relevant natural phenomena and their impact on the geological environment.

Finally, Section 3.5 summarises key conclusions from this chapter and discusses future actions.

3.1 The role of the geological environment in ensuring repository safety

3.1.1 Requirements on the geological environment and associated influencing factors

(1) Requirements and conditions for ensuring safety before closure (during construction and operation)

Starting from the literature survey (LS), selection of the repository site proceeds through staged siting investigations (for details, see Section 3.2.3), which are then followed by a series of tasks related to the construction, operation and closure of the repository (see Chapter 4 for details). These tasks include construction of the surface and underground facilities, acceptance and inspection of the waste and encapsulation in overpacks, emplacement of the waste and construction of an engineered barrier system (EBS), and, finally, backfilling and sealing of the repository. Table 3.1-1 summarises the requirements[1] ([1] and [2]) for the geological environment from the viewpoint of performing these tasks, with safety as the highest priority.

Table 3.1-1 Requirements and influencing factors for the geological environment until closure

Requirements for the geological environment	Influencing factors[*1]
The host rock must not be unconsolidated Quaternary sediments	Distribution of unconsolidated Quaternary sediments at depths of 300 m or more … (1)
Events that affect the safety and operability of the underground facilities are unlikely to occur	Geothermal activity/hot springs[*2], swelling ground, rock burst, mud volcanoes, high water inflow, toxic gas, earthquake activity... (2)
Events that would disrupt the safety of the surface facilities are sufficiently unlikely to occur	Pyroclastic flow, lava flow, lahar... (3)
Events that could negatively impact the safety of the surface facilities are unlikely to occur	Distribution of soft ground, ground deformation and displacement, occurrence of earthquakes, tsunamis, landslides, debris flows, floods... (4)

[*1] The policy for selecting a site considering each of the influencing factors (1) to (4) is presented in Section 3.1.2.
[*2] Refers to warm or hot water upwelling from underground.

(2) Requirements for ensuring long-term post-closure safety

The basic concept for ensuring long-term safety after closure of the repository involves "isolation" and "containment", as described in Sections 2.1.2 (1) and (3). In order to achieve this, the geological environment is expected to maintain the following functions over a long period of time [3] [4] (as shown in Table 3.1-2.):

- Protection from significant effects of natural perturbing phenomena.
- Reduction of the likelihood of human intrusion.

[1] Not only the requirements defined in the Final Disposal Act and the Advisory Committee for Natural Resources and Energy (2017) [2], but also the conditions considered to be favourable, are included as "requirements" in this report.

- Restriction of RN leaching.
- Restriction of RN migration.

In particular, from the viewpoint of the functions related to the restriction of the release and transport of radionuclides, the requirements on the geological environment for assuring EBS performance and acting as a natural barrier [5] [6] can be summarised in terms of favourable thermal, hydraulic, mechanical, and chemical (THMC) conditions [1] [2], with a focus on HLW.

Table 3.1-2 Requirements for the long-term post-closure geological environment (Modified from IAEA, 2011 [3]; 2011 [4] and Advisory Committee for Natural Resources and Energy, 2017 [2])

Basic concept	Safety function	Requirements for the geological environment
Isolation	Protection from significant effects of natural perturbing phenomena	Natural phenomena that would cause the waste to approach, or be exposed to, the biosphere will not occur over relevant timescales
	Reduction of the likelihood of human intrusion	Mineral resources with high economic value are not identified
Containment	Restriction of RN leaching and Restriction of RN migration	Thermal environment: The rock temperature is sufficiently low so that a loss of function resulting from thermal degradation of the buffer material due to long-term exposure to temperatures higher than 100 ºC will not occur
		Hydraulic environment: Groundwater flow is slow due to a low hydraulic gradient and/or low hydraulic conductivity, which assures EBS longevity, increases the transport time of radionuclides with groundwater flow and reduces the concentration of radionuclides due to radioactive decay
		Mechanical environment: Rock deformation is small due to high compressive strength and elastic modulus and small creep deformation to prevent damage to the overpack
		Chemical environment: Groundwater satisfies conditions of no extreme pH, is chemically reducing and carbonate concentration below 0.5 mol/l [2] to suppress: dissolution of glass, local corrosion and passivation of overpack, alteration of buffer material a decrease in sorption capacity of buffer material and bedrock, an increase in solubility of radionuclides

Japan is located in the Circum-Pacific Orogenic Belt, as described in Section 3.1.3 (1), so natural disruptive phenomena, such as volcanic/igneous activity, earthquake/fault activity, and uplift/erosion occur, repeatedly or continuously on a geological timescale of hundreds of thousands to millions of years. The characteristics of these phenomena, based on scientific knowledge and the results of case studies obtained up to the time of JNC's H12 report [7], have been reconfirmed [1] in the latest compilation of scientific knowledge [8]. Such natural phenomena may affect the safety functions expected for the geological environment [1] [2] [7]. Especially when there is a "significant impact" [1] [9], which exceeds the range that can be handled by the repository design, the safety functions expected for the geological environment could be significantly reduced or lost [10].

Even in geological environments where such natural phenomena are not significant, various perturbations could occur within the repository during relevant timescales, such as the slow and cumulative effects of unavoidable phenomena, such as uplift/erosion and sea-level changes, on timescales exceeding tens of thousands of years. Such intrinsic or extrinsic perturbations and associated effects are suppressed by the natural buffering function of the geological environment [5] [6]. Deep underground, geological characteristics change slowly over time, and sudden or fast changes are thus unlikely [11]. Taking into account the extent of such changes, the geological environment can be considered to show sufficient stability when favourable characteristics for repository safety are maintained for a long enough time [5] [6]. As described in section 3.1.3 (2), if this stability can be justified based on scientific knowledge of relevant events and processes that have occurred from the past, it is considered that the probability of reducing or losing the function of restricting the release and migration of radionuclides is extremely small [11] [12] for periods exceeding around 100 ky in the future, by which time the hazard presented by the waste has decreased significantly due to radioactive decay.

In Table 3.1-3, factors affecting the expected long-term post-closure safety function of the geological environment and key processes involved are summarised [1] [2].

Table 3.1-3 Impact on long-term post-closure safety functions expected for the geological environment and influencing factors (edited from Advisory Committee for Natural Resources and Energy, 2014 [1]; 2017 [2])

Influencing factors and main processes[*1]		**Effects on safety functions**
Volcanic and igneous activity	Magma intrusion and eruption at the surface... (5)	Release of waste to the biosphere
Migration and inflow of volcanic hydrothermal and deep-seated fluids[*2]	Movement and inflow of volcanic hydrothermal and deep-seated fluids... (6)	Rise in ground temperature
		Decrease in groundwater pH or increase in carbonate species concentration
Earthquake and fault activity	Displacement of a fault reaching the surface from deep underground … (7)	Breaking and crushing of the rock mass
	Increased hydraulic conductivity of the rock mass around a fault and infiltration of oxidising surface water... (8)	Change in groundwater flow paths and change of groundwater to oxidising conditions
Uplift/erosion[*3]	Significant decrease in overlying rock mass thickness … (9)	Approach of waste to the biosphere
	Continuous changes in topography and sea-land distribution … (10)	Slow, long-term changes in groundwater flow paths and groundwater chemistry
Existence of mineral resources	Mining of high economic value mineral resources... (11)	Human intrusion into the repository

[*1] Policy on site selection corresponding to each of the factors (5) – (11) is described in Section 3.1.2.
[*2] Movement and inflow of volcanic hydrothermal and deep-seated fluids includes geothermal activity associated with magma and hot rock.
[*3] Effects of climate and sea-level changes are considered as erosion factors.

The table also lists factors that may result in unintentional human intrusion in the future, for example as in Section 3.1.2 (2), although the existence of mineral resources is not considered as a “disruptive phenomenon”.

3.1.2 Approach to using influencing factors in site selection

(1) Factors influencing pre-closure safety

For factors affecting the pre-closure safety of the repository, the basic approach described in Section 2.2.1 is applied, as outlined in Table 3.1-4 (together with those factors impacting long-term post-closure safety presented in (2) below).

Table 3.1-4 Basic approach to site selection for factors influencing safety

Influencing factors (See Tables 3.1-1 and 3.1-3 for numbers)		Basic approach to site selection	Literature study	Preliminary Investigations	Detailed Investigations
			Spatial scale: ■ Regional ■ Repository ■ Panel		
(1)	Distribution of unconsolidated Quaternary sediments	• Exclude areas where unconsolidated Quaternary sediments are distributed at a depth of 300 m or more	Regional	Regional, Repository	Repository
(2) - (4)	High geothermal gradients, hot springs, earthquakes, tsunamis, distribution of soft rock, rock deformation and displacement	• Understand the extent of impacts during the operational phase • Apply suitable construction technologies and consider the location of the surface facilities in order to reduce potential impacts	Regional	Regional, Repository	Repository, Panel
(3)	Pyroclastic flow, lava flow, lahar	• Understand the possible extent of impacts during the operational phase • Consider the location of the surface facilities to avoid an impact	Regional	Regional, Repository	Repository
(5) - (9)	Volcanic and igneous activity, presence of volcanic hydrothermal fluids and deep-seated fluids, seismic and fault activity, uplift and erosion	• Exclude areas with significant effects • Exclude areas with poor geological environment characteristics	Regional	Regional, Repository	Panel
(6) - (8) (10)		• Understand long-term changes in the geological environment characteristics due to slow effects • Examine appropriate engineering measures minimising such impacts • Confirm that the function of restricting the release and migration of radionuclides is maintained for a sufficiently long time • Exclude the site from the selection if the function of restricting the release and migration of radionuclides cannot be assured	Regional	Regional, Repository	Repository, Panel
(11)	Existence of mineral resources	• Exclude areas where minerals of high economic value exist	Regional	Regional, Repository	

In terms of the factors in Table 3.1-1, for (1), areas with unconsolidated Quaternary sediments at depths greater than 300 m are excluded because it is considered that construction, maintenance and operation of the underground facilities will be difficult [2] in such cases. For (2) and (4), responses and safety measures in facility design are examined based on past measures for existing nuclear facilities and other relevant underground structures in order to reduce impacts on the target formation, surrounding rocks or the site in general (for details, see sections 4.5 and 4.6). For (3), if it is impossible to resolve issues by robust design of the surface facilities [2], the location of these facilities is determined considering the extent to which events related to volcanic activity, such as pyroclastic flows, are likely to occur during the operational period.

(2) Factors influencing post-closure safety

For factors affecting long-term post-closure safety, the stepwise site investigation process described in Section 3.2.2 will be conducted according to the basic concept presented in Section 2.2.2. Based on the results, when significant effects are expected from processes (5) and (9) in Table 3.1-3, or when their impacts may become significant in the future, the areas of influence will be excluded [1] [2] because the geological environment cannot provide long-term protection from disruptive events. Similarly, when significant effects are expected as a result of processes (6) - (8), or when their impacts may become significant in the future, the areas involved are excluded [1] [2] because the geological environment cannot be expected to perform the function of long-term restriction of the release and migration of radionuclides.

For areas where no significant effects from natural perturbations are expected, now or in the future, impacts of processes (6) - (8) are assumed. As for the slow and cumulative effects of unavoidable natural phenomena ((10) in Table 3.1-3), appropriate engineering measures depending on the degree of the impact will be considered, taking the expected long-term changes in the geological environment into account. It is then confirmed that the function of restricting the release and migration of is maintained for a sufficiently long time. If the results indicates that long-term confinement in the geological environment cannot be assured, the site is excluded from the selection candidates.

As noted in (11), areas where economically valuable mineral resources exist underground are excluded because exploration and mining that may be conducted in future could lead to humans coming into contact with the waste as a result of inadvertent human intrusion. The economic value and existence of mineral resources are judged by considering the issue of mining rights according to the applicable Mining Law, but additional considerations may be applied later, as it is recognised that the future value of mineral resources is difficult to judge. In addition to valuable mineral resources, evaluation of effects from geothermal resources, hot springs and groundwater resources will continue after the Preliminary Investigation Areas have been selected [2].

Based on the policy for site selection described above, the selection process is conducted in three stages as shown in Table 3.1-4. Suitable geological environments are thus identified. The spatial scale corresponding to each stage of investigation is as described in Section 2.2.3 and Figure 2.2-2.

3.1.3 Selecting a geological environment suitable for geological disposal in Japan

(1) Features of geological environments in Japan

The Japanese islands form an arc-shaped archipelago that extends from northeast to southwest on the eastern margin of Eurasia. It is located on a plate convergence boundary where oceanic plates (Pacific and Philippine Sea plates) subduct below continental plates (Eurasian and North American plates). The current consensus is that the formation of the Japanese archipelago in its present form [13] was closely related to changes in the plate layout and movement patterns. The early form of the archipelago was formed around 30 to 15 My ago, along with marginal seas such as the Sea of Japan, the Chishima Basin and the Shikoku Basin. Subsequent plate subduction continued in almost the same positions, with the direction of movement of each plate set in the current pattern about 2 My ago [13] [14]. In the Japanese archipelago, volcanic/igneous activity, seismic/fault activity and uplift/subsidence occur due to such plate movements. These natural phenomena are typical for a tectonic belt distributed along a plate convergence boundary and occur repeatedly or continuously on a geological time scale of hundreds of thousands to millions of years. In addition, global climate and sea-level changes impact erosion and sedimentation.

The following summarises the main scientific understanding of natural phenomena in Japan. Supporting Report 3-1 summarises the situation as presented in the H12 report [7].

(i) Volcanic and igneous activity

Volcanic and igneous activity due to plate subduction is unevenly distributed. On the arc/volcanic line scale (hundreds to tens of kilometres), the position of the volcanic front has not moved significantly over the past several My [7] [8]. In northeast Japan, Quaternary volcanic activity occurs repeatedly in the back-arc region of the volcanic front, with areas where volcanoes are densely located clearly distinguished from areas where there are no volcanoes [15] [16]. Areas of volcanic activity are controlled by finger-like, high-temperature areas with a width of about 50 km (called “hot fingers”), which are considered to be stable for a long time and associated with magma bodies deep underground [17] [18]. In southwest Japan, although the volcanic front is not as clearly defined, Quaternary volcanic activity tends to be restricted to areas closer to the Sea of Japan than to the Chugoku Mountains [19].

Regarding the extent of magmatic activity, with the exception of huge caldera volcanoes and monogenetic volcanoes, individual volcanic vents (side volcanoes) that make up the Quaternary volcanoes [20] [21] are generally distributed within a radius of about 15 km around each Quaternary volcanic centre [22]. However, cases in which dyke magmas migrate more than 30 km from the centre of Quaternary volcanoes have also been identified [23].

(ii) Migration and inflow of volcanic hydrothermal and deep-seated fluids

According to correlation diagrams, the pH of groundwater and hot spring water [24], within around 15 km from the centre of a Quaternary volcano is often acidic, with pH below 4 due to dissolved volatile components such as SO_2, H_2S and HCl released from magma. Geothermal water convection is closely related to volcanic and other igneous activity. High-temperature anomalies with a geothermal gradient exceeding 10 °C/100 m is highly correlated with the uneven distribution of the aforementioned Quaternary volcanoes [25] [26].

However, in non-volcanic areas such as the Joban region, the Noto Peninsula, the Niigata Plain, the Kii Peninsula, Arima Onsen and the northern Shikoku region, thermal water of non-volcanic that does not originate from underground magma and non-meteoric fluids with high salinity or high carbonate concentrations are distributed [27] [28] [29] [30] [31] [32]. These deep-seated fluids include waters of deep subducted slab or mantle origin that have arisen through fracture systems and mixed with groundwater (for example, Arima type hot water) or oilfield porewater, in a formation that has been stagnant for a long time.

(iii) Earthquake and fault activity

Seismic/fault activity has not only occurred repeatedly in response to regional compressive stress fields since the Quaternary [33] [34], but has also occurred due to the effects of stress changes associated with mega-thrust earthquakes such as the 2011 Tohoku Earthquake [35] [36]. “Active faults” with large displacements that are repeatedly active and can be confirmed at the ground surface are compiled in geological databases [37] [38] [39] [40] [41]. Given that new active faults are sometimes detected after the occurrence of an earthquake, it is possible that an active fault exists underground, although not confirmed at present [39], because any surface displacement is not evident or has been overlooked [26]. As a specific example of this, surveys conducted after the occurrence of large-scale inland earthquakes (such as the Tottori Prefecture Seibu Earthquake in 2000 and the Iwate-Miyagi Nairiku Earthquake in 2008) confirmed relevant underground structures related to surface ruptures and earthquake source faults in areas where no active fault had been identified previously [42] [43] [44].

The range of influence due to fault movement is defined by the width of the process zone, which is about 1% of the fault length. In this area, the fracture density is higher than the surrounding host rock outside the fault zone [45] [46] [47]. Around a large active fault, other faults nearby may be reactivated, or areas of fault activity may expand to include multiple faults [48] [49] [50].

(iv) Uplift, subsidence and erosion

Uplift and subsidence are ongoing over the last several hundred thousand years with a pattern resulting from regional tectonic activity. Especially in areas where crustal deformation is active, significant linear erosion can be caused by rivers (exceeding 50 m in the last 100 ky). In the Central and Southern Alps, it has been confirmed that significant denudation (in the order of kms) has occurred since the Late Pliocene (≈ approximately 3 My ago) [51] [52] [53]. The current uplift rate in the Northern Alps can be as high as 5-6 m/ky [54].

In general, erosion and uplift rates in the mountains and hills reach equilibrium in 100s ky to about a My [55]. In the upper to middle basins of rivers, erosion and uplift in a glacial cycle almost balance out [56]. In coastal regions, sedimentation has continued since the Neogene in some areas, while in other areas this was replaced by uplift in the Late Quaternary [57] [58] [59] [60] [61]. Close to river estuaries within uplift areas, since the Late Pleistocene the undercutting rate during one glacial cycle exceeds the amount of uplift, with a maximum value of about 100 m [62]. In terms of climate and sea-level changes that cause erosion [63], a key factor is the drop in sea-level of up to 150 m during glacial periods [64].

As an oceanic plate subducts below a continental plate, accretionary complexes (wedges/prisms) of various ages accumulate along the boundary of the plates, the position of which may change with time. The Japanese archipelago is generally characterised by basement that is older on the continental side and younger on the Pacific side [26]. The geology of the archipelago is composed of various types of strata and rocks (Geological Society of Japan, 2011) [26]. From the viewpoint of clarifying geological features that are important for site selection, the geology (Geological Society of Japan, 2011) [26] can be subdivided into seven categories; Quaternary sedimentary rocks, Quaternary volcanic rocks, Neogene and Pre-Neogene sedimentary rocks, Neogene/Pre-Neogene volcanic rocks, Neogene/Pre-Neogene plutonic rocks, and metamorphic rocks, as shown in Figure 3.1-1. The Pre-Neogene sedimentary and metamorphic rocks and the Neogene/Pre-Neogene plutonic rocks that intrude into them, form the basement, which is covered by Neogene and Quaternary sedimentary rocks and volcanic rocks that erupted at various times, or is exposed in some areas.

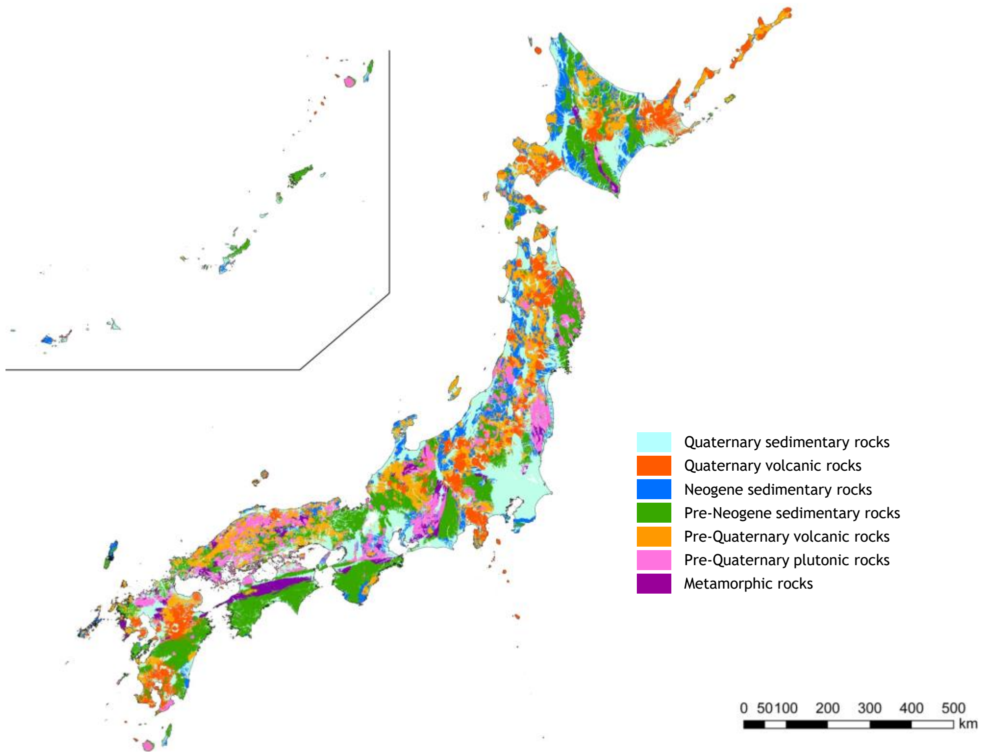

Figure 3.1-1 Geological map of the Japanese archipelago (Based on AIST 1: 200,000 Japan geological map [65])

Due to the tectonic conditions noted above, Japan has large topographic relief, with most of the archipelago covered by mountains and hills. At many locations, the mountains/hills extend very close to the coast. With a relatively warm climate, abundant precipitation and geographical features typical for a marine archipelago, the groundwater table is generally high. Underground formations and rock masses are thus saturated with groundwater up to near the ground surface. The groundwater chemistry varies over a wide range, depending strongly on its origin, the type and hydraulic conductivity of formations and rocks in contact with evolving water, as well as the spatial distribution of topography and geological structures that control groundwater flow [66]. In inland areas, not only groundwater of meteoric origin but also magma-derived groundwater in volcanic areas and deep-seated fluids rising through fault systems are identified [28] [29] [30] [31] [32]. In coastal areas, both meteoric groundwater extending under sea areas and intrusion of saline groundwater into freshwater aquifers are seen. Deep, old seawater (fossil seawater or oilfield brine), reflecting stagnation in formations for tens of thousands to millions of years, generally shows a complex areal distribution [67] [68] [69].

Closely related to the evolution of geological environments, resources such as coal, oil and natural gas, as well as various metal and non-metal minerals, are known in specific locations [70] [71] [72] [73].

(2) Environments with favourable characteristics from the viewpoint of geological disposal

Characteristics of the deep geological environment in Japan, in terms of requirements from the viewpoint of waste confinement shown in Table 3.1-2, are summarised in Table 3.1-5 [8].

Table 3.1-5 Favourable geo-environmental characteristics widely found deep underground in Japan (Modified from Advisory Committee for Natural Resources and Energy, 2014 [1])

Requirements for the geological environment		Common characteristics of the geological environment
Thermal environment	Low rock temperature	Geothermal gradient is generally 3 - 5 °C/100 m, except for higher values associated with volcanic areas
Hydraulic environment	Slow groundwater flow	Hydraulic gradient at relevant depths is generally in the order of 0.001 to 0.01. Hydraulic conductivity is in the order of 10^{-12} to 10^{-6} m/s and decreases with depth. Larger hydraulic gradients may occur in lower hydraulic conductivity rock
Mechanical environment	Small rock deformation	Deep rock generally has high compressive strength and elastic modulus, such that long-term creep is within the range that can be handled by repository design
Chemical environment	Groundwater pH not extreme, chemically reducing, carbonate concentrations less than 0.5 mol/l	Deep groundwater generally has a pH of 6 to 9, with reducing conditions and carbonate concentrations less than 0.1 mol/l

Geological environments in Japan have been identified in which favourable geological disposal characteristics have been maintained over a long period of time. Through research based on natural analogues and paleo-hydrogeology, focusing on evidence preserved in groundwater, rocks and minerals (record of paleo-hydrogeological evolution), favourable hydraulic and chemical conditions have been shown to persist for a long time, despite continuous or periodic uplift/erosion and climate/sea-level changes.

Examples of relevant studies are summarised below.

- At several hundred metres below sea-level in the Horonobe area of Hokkaido, Quaternary sedimentary rock contains groundwater recharged during the glacial retreat, tens of thousands of years ago [67] [68] [69]. This is interpreted as being related to movements of the saltwater/freshwater boundary caused by glacial cycle sea-level fluctuations [61]. In addition, deeper Neogene sedimentary rocks have a low hydraulic conductivity [74] and retain paleo-oceanic formation water with an age (residence time) of several My [75]. In such a closed environment, a reducing environment would persist as a result of continued water-mineral-organic-microorganism interactions [76].

- In Neogene sedimentary rocks in the Yokosuka area of Kanagawa Prefecture and in Cretaceous sedimentary rocks (classified as Pre-Neogene sedimentary rocks) in the Kushiro area of Hokkaido, ancient groundwater is found with a residence time of at least ≈ 7 My and ≈ 2 My or more, respectively [77] [78]. These formations mainly consist of mudstone and shale, with groundwater flow being extremely slow in such low hydraulic conductivity formations.
- Neogene sedimentary rocks, including the uranium deposits in the Tono area, Gifu Prefecture, have been affected by natural phenomena such as faulting, uplift/erosion, and sea-level changes. Despite this, uranium deposits have been preserved for as long as 10 My [79]. It is considered that the uranium did not dissolve because groundwater pH and a reducing environment were maintained as a result of water-mineral-microbial interactions so that the redox front near the surface is almost static. [80].
- Cretaceous granites (classified as Neogene and Pre-Neogene plutonic rocks) in the Tono area of Gifu Prefecture indicate some changes in the chemical environment with time. This is confirmed based on changes in calcite crystals on the fracture surface (groundwater flow paths) and the heterogeneous distribution of some trace elements. However, no significant change in the redox environment was observed and reducing conditions were assumed to have been maintained deep underground [81].
- At the Adera fault[2] in Central Japan, although oxidising surface water infiltrated due to past uplift, its hydraulic and chemical impact was limited [82] [83]. Iron hydroxide and calcite were formed in the damaged zone around the fault, which is a focus for groundwater flow and mass transfer. Such iron hydroxide and calcite lead to a reduction in hydraulic conductivity due to clogging (blocking rock porosity) and results in persistence of the pH and reducing environment due to chemical buffering [82] [83].

Thus, there are areas deep underground in Japan where geological environments with favourable characteristics have been confirmed, and therefore it is reasonable to assume that such areas are widely distributed. By avoiding areas showing significant effects of natural perturbations and assessing the temporal and spatial stability of key characteristics of the volunteer sites[3], it is considered possible to identify environments suitable for geological disposal in Japan, despite its location in an orogenetic belt. The specific procedure for determining suitable geological environments is described in the next section.

3.2 Process for identifying environments suitable for geological disposal

3.2.1 Basic strategy and methodology

In geological disposal, it is essential to select a geological environment where the safety functions will be maintained for a sufficiently long time. For this purpose, NUMO will

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[2] Although the Adera fault is an active fault, it is described as one of the cases related to the buffering of hydrological and chemical changes observed in the vicinity of the fault.

[3] In this report, the areas that applied for a literature survey and the areas that accepted a proposal for a literature survey from the Japanese government are collectively described as “the volunteer sites”.

proceed with stepwise site selection based on the concept of building understanding of geological events and processes that have occurred in the past, thus forming the basis for understanding of those occurring now and in the future. Specifically, following a site assessment policy based on factors affecting safety as described in Section 3.1.2, the spatial scale of potential siting areas and the relevant geological events and processes to be investigated are narrowed down through the stages of literature survey (LS), preliminary investigations (PI), and detailed investigations (DI). The geological investigations and evaluations are conducted with a gradually increasing level of detail. Site selection is thus implemented as follows:

- Clearly unsuitable sites, owing to distribution of Quaternary unconsolidated deposits, existence of mineral resources or risks of perturbation due to impacts of volcanic activities, migration and inflow of volcanic hydrothermal and deep-seated fluids, earthquake/fault activities and uplift/erosion, are excluded. The basic concept for investigation/evaluation of natural perturbations is presented in Supporting Report 3-2, and the specific approaches involved for volcanic/igneous activity, earthquake/fault activity, and uplift/erosion are presented in Supporting Report 3-3, Supporting Report 3-4, Supporting Report 3-5. The current status and research and development (R&D) issues related to the methods for evaluating the effects of natural perturbations, as well as the combination of individual technologies that make up the investigation/evaluation programme, are presented in Supporting Report 3-6.
- For sites where significant effects of natural phenomena can be avoided, the characteristics of the geological environment from the viewpoint of confinement of the waste are evaluated, and areas that are clearly less suitable can be excluded. It is necessary to consider the effects of slow, cumulative processes, such as uplift and erosion, such characteristics. For this reason, past temporal and spatial changes of the geological environment will be examined. By quantifying the range of variations through modelling, NUMO aims to confirm that favourable characteristics are stable enough to support sufficient barrier performance in excess of 100 ky. The basic approach and workflow for investigation and evaluation of the geological environment are presented in Supporting Reports 3-7 and 3-8. The current status and research and development (R&D) issues relating to methodology, as well as the combination of individual technologies that make up an integrated programme are identified in Supporting Report 3-9. An approach for assessing long-term changes in geological characteristics is presented in Supporting Report 3-10. In addition to the effects of natural perturbations, individual investigation and evaluation technologies related to geo-environmental characteristics and their long-term changes are summarised in Supporting Report 3-11.
- Particularly for the 100 ky timescale, it is necessary to consider events that could have a significant effect on the safety functions of the repository even if their likelihood of occurrence is extremely small. The uncertainties in the occurrence of events and their effects on the geological environment are evaluated using a combination of extrapolation and stochastic methods, taking into account limitations of the associated knowledge base. This is described in detail in Section 3.2.2 (2).

At each stage of the site selection process, following assessment of eligibility in terms of statutory requirements and siting factors, NUMO will examine repository concepts tailored to the site to confirm engineering feasibility and post-closure safety. This will allow identification of further information to be acquired on the geological environment, the level of detail needed, and the methods to be applied in order to reduce uncertainties resulting from the lack of information or how it is interpreted. Although the items to be investigated/evaluated will depend on site conditions, examples are listed in Table 3.2-1 based on experience accumulated in Japan and overseas [84] [85] [86].

Table 3.2-1 Examples of geological investigations/evaluation topics for sites

Purpose of survey/evaluation	Survey/evaluation items	
Avoiding impacts of natural perturbations to ensure operational and post-closure safety	Volcano and igneous activity	• Probability and extent of magma movement from Quaternary volcanoes • Probability and extent of new volcanoes (magma chamber development)
	Volcanic hydrothermal and deep-seated fluids*	• Potential extent of thermal and chemical effects of future thermal fluid inflow
	Earthquake and fault activity	• Distribution of active faults and potential future activity • Extent of hydraulic and mechanical impacts associated with fault movement • Changes in the geological environment due to seismic activity
	Uplift and erosion	• Future uplift/subsidence rate • Future erosion rate and long-term topographic changes • Climate/sea level change
Confirmation of engineering feasibility and Assurance of post-closure safety	Geological structure	• Geometry of geological structures relevant to groundwater flow paths • Geometry of strata and rock bodies as potential host rocks • Spatial distribution of lithological discontinuities and fractures in strata and rock bodies • Geometry of water-conducting microstructures influencing nuclide migration
	Thermal environment	• Geothermal gradient • Thermal characteristics of strata and rock bodies
	Hydraulic environment	• Spatial distribution of hydrogeological structures • Spatial distribution of groundwater flow • General hydraulic characteristics of strata and rock bodies • Hydraulic properties of water-conducting structures • Gas migration characteristics of strata and rock bodies • Gas migration characteristics of preferential flow structures • Spatial distribution of hydraulic head and water temperature • Solute migration characteristics of water-conducting microstructures
	Mechanical environment	• Physical characteristics of strata and rock bodies • Physical characteristics of faults and fractures • Mechanical characteristics of strata and rock bodies • Mechanical characteristics of faults and fractures
	Chemical environment	• Spatial distribution of groundwater chemistry and tracer isotopes • Spatial distribution of groundwater pH/Eh (oxidation-reduction potential) • Properties and distribution of gas in groundwater • Properties and distribution of gas in strata and rock bodies • Chemical effects of colloids, organic substances and microorganisms • Solute retardation characteristics of water-conducting microstructures
	Long-term evolution of geological characteristics	• Evolution of regional stress field • Topographical and geological structure evolution • Temporal changes in groundwater flow and hydraulic properties • Evolution of factors controlling groundwater chemistry • Temporal changes in thermal, physical and mechanical properties of strata and rock bodies

*The movement of volcanic hydrothermal fluids include geothermal activity associated with both magma and other deep rocks.

Information obtained through site investigations is interpreted using a multidisciplinary approach to construct a common conceptual model of the site geology (SDM). The current geological environment, such as spatial distribution and geometries of geological formations/rock bodies/geological structures, their thermal/hydraulic/mechanical characteristics, and the spatial distribution of groundwater chemistry (as listed in Table 3.2.1) are represented (visualised) within the SDMs. Temporal changes in such characteristics are also conceptually modelled. Figure 3.2-1 shows an example of a SDM.

Such a SDM allows repository concepts to be developed, in terms of both repository design and the associated safety assessment, and further requirements for future geological characterisation to be identified. Thus, NUMO will conduct iterative site investigation while repeating the examination of the repository concepts based on the updated knowledge base captured in the SDM.

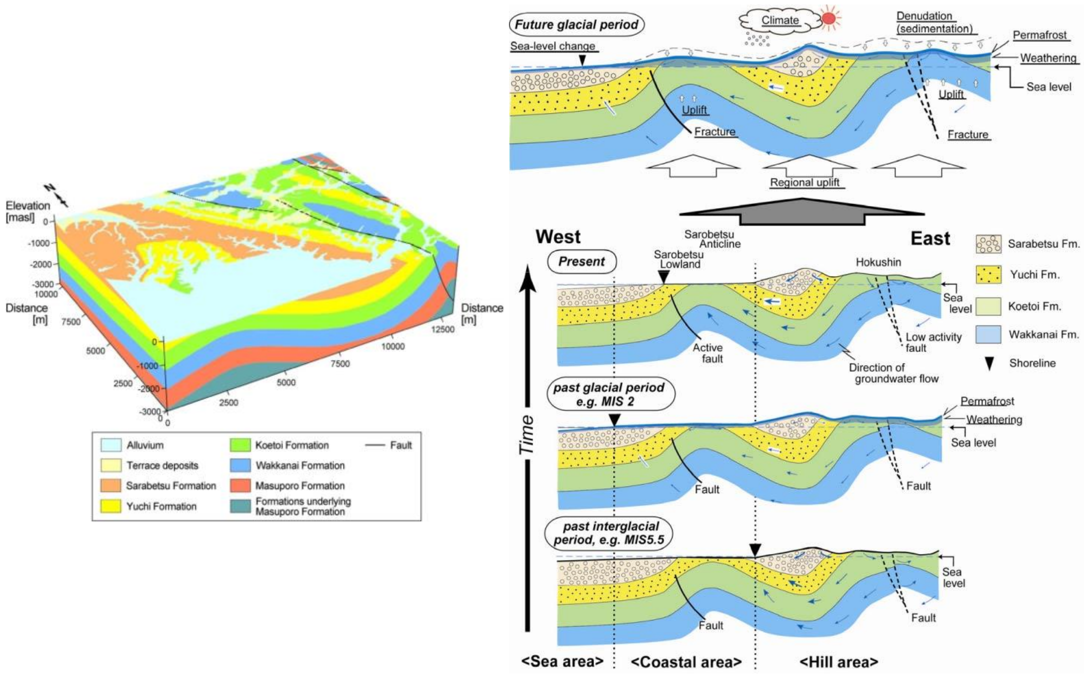

Figure 3.2-1 Example of a SDM constructed based on geological investigations & evaluations. Left: Geological model (Ota et al., 2007 [74]), Right: Conceptual model of long-term changes of the geological environment (Niizato et al., 2010 [87])

When conducting the iterative site investigations described above, the reliability of the safety assessment depends on the range, quantity and quality of the acquired geological information [4]. In the site investigations, as noted in Section 2.5.2, quality management of the series of work processes from acquisition to interpretation of geological information is indispensable, as is recognised internationally [88]. Specifically, applying practical quality control/assurance concepts as captured in documents [89] [90] currently being developed, consistent quality management can be implemented during each of the stages of the site selection process. At each stage, NUMO will confirm that not only that the report of the investigation and evaluation results is prepared in accordance with the Final Disposal Act Enforcement Regulations, but also the resultant SDM meets the specified requirements. Supporting Report 3-12 describes, for the example of the PI stage, an outline of the documents related to quality control/assurance for investigations on land (inland/coastal) and offshore areas, as well as the associated construction of the SDM.

The details of the basis for the staged site investigations are described below.

(1) Reduction of uncertainty using an iterative approach

The investigations target geological environments with heterogeneous characteristics, evolving over an extremely long timescale, and hence data and their interpretation include temporal and spatial uncertainties. Handling such uncertainties is one of the most important issues, not only in evaluating the probability of occurrence of natural perturbations and their range of influence, but also in evaluating the spatial distributions of geological characteristics and their temporal changes [4]. Geological factors with high uncertainty (e.g. spatial distribution of faults and hydraulic characteristics) are thus a special focus during site investigations. When SDMs are developed for specific sites, information on key uncertainties will be passed on to the repository design and safety assessment teams as an inherent component of the SDM (and associated data set). Feedback from these teams will thus allow NUMO to focus future work on the more significant geological factors. Based on this, and following the basic concept for planning site investigations and evaluations [91], a plan is developed to reduce such uncertainties by refining the targets and priorities set for the next stage (as indicated in Sections 3.2.2 (2) and 3.2.2 (3)).

In the JAEA Mizunami Underground Research Laboratory (URL), the effectiveness of such an iterative approach for reducing uncertainty has been illustrated, with developing site investigations leading to refinement of the associated SDM [74] [92]. In terms of the geological structures present, more detailed information on the distribution of formation boundaries, faults and fracture zones is acquired as the investigations progress and visualised in the evolving SDM. Examples in which the understanding of the geological structures has been developed through this approach are presented in [92] [93] [94] [95]. For groundwater flow in particular, the influence of the uncertainty in fault hydraulic conductivity is evaluated, and the results are reflected in the investigation plan for the next stage, allowing such uncertainty to be gradually reduced during the progress of investigations [92].

Furthermore, such an iterative approach has been adopted in site investigations overseas. For example, during Posiva's investigation at the Olkiluoto site in Finland, studies from the ground surface and subsequent investigations in the Onkalo underground rock characterisation facility (RCF) were implemented in stages, with progressively increasing detail. In conjunction with updating the SDMs in areas such as structural geology of the host rock, rock mechanics, hydrogeological structures and groundwater geochemistry, the associated reductions in uncertainty and improvements in reliability have been evaluated [96] [97] [98] [99]. A similar approach was followed for investigations conducted by SKB at the Forsmark site in Sweden [100] [101] and those conducted by Nagra at the Wellenberg site in Switzerland [102] [103].

As site investigations progress, the significance of residual uncertainties in terms of design or safety generally decreases. However, it is possible that new facts and new uncertainties will be identified by iterative geological investigations. Therefore, a decision to end site investigations is made only if sufficient quality and quantity of geological environment information has been gathered to meet requirements and any newly acquired information does not impact the associated safety assessment.

(2) Use of the SDM to integrate repository design and safety assessment

It is important to store the information obtained from the geological investigations in a format that can be used for disposal site design and safety assessment, sharing the resultant site understanding as well as associated uncertainties. As described earlier, SDMs are constructed in which the current state of the geological environment is visualised in three dimensions. The characteristics include the spatial distribution and geometry of geological formations, rock bodies, and geological structures, together with associated thermal, hydraulic, and mechanical properties, as well as the spatial distribution of groundwater chemistry. Temporal changes in these geological characteristics are also modelled.

In order to effectively and efficiently progress from the site investigations to the production of the SDM, a “geosynthesis” methodology will be used [85] [92] [104]. Specifically, for the geological environment on the target spatial scale, relevant issues related to its characteristics will be defined (as shown in Table 3.2-1) and these assessed, together with their long-term evolution. These are then incorporated into the SDM that include a sufficient range of credible evolution scenarios. To understand these items properly, geological information obtained from the investigations is interpreted based to produce conceptual models of geology and geological structures, considering both multi-disciplinary consistency and continuity between different scales. Based on these, the SDM is further developed, incorporating the spatial distribution of formations and rock bodies in 3D, together with major faults and lithostratigraphy. Using this as a common basis, models of hydrogeology, groundwater chemistry and rock mechanics models are integrated within it. By applying the iterative approach described above, the effects of uncertainty of data and lack of understanding of the geological environment on the design and safety assessment of the repository at any stage (or phase) can be assessed. Thus, the focus for geological characterisation in the next stage (or phase) can be narrowed down, and the investigation plan optimised.

Such geosynthesis allows the comprehensive knowledge base developed by site investigations [74] [84] [92] [105] to be effectively captured for site-specific conditions. This knowledge base can be managed by advanced tools – such as the next-generation site characterisation Information Synthesis and Interpretation System (ISIS) developed by JAEA [105]. For each investigation scale and stage, this includes not only integrated data flow guidance to systematically organise links between various investigation, data acquisition, data interpretation, and data integration (modelling/analysis) processes, but also to summarise the technical knowledge and know-how obtained.

Such a method of integrating geological environment information (or methods based on a similar approach) has been widely applied to overseas site investigations [99] [101] [103] [106] [107] [108]. It is considered to be particularly useful in facilitating use of geological information for constructing a safety case [104], by linking site investigations to repository design/safety assessment. This method was applied in JAEA's URL projects at both Horonobe and Mizunami, and its effectiveness has been shown during optimisation of the underground construction on the basis of SDMs [74] [92]. Figure 3.2-2 shows a concrete example of a SDM constructed by integration of geological information from JAEA's URL project in Mizunami.

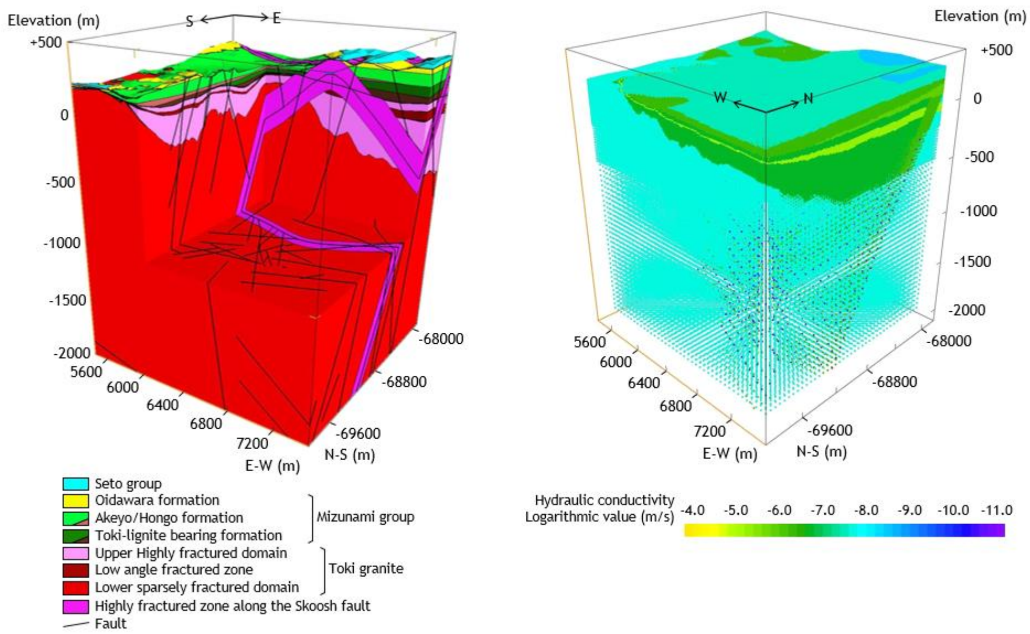

Figure 3.2-2 Example of a SDM for the area around the Mizunami Underground Research Laboratory. Left: geological model showing the spatial distribution of geological structures. Right: hydrogeological model showing the spatial distribution of hydraulic conductivities for geological structures (Modified from Saegusa et al., 2007 [92])

In Section 3.3, the processes and results of stepwise SDM construction are described in detail.

3.2.2 Stepwise implementation of site investigations

NUMO has developed workflows based on the staged site investigation procedure described in Section 3.2.1 [109]. As noted in Section 1.2, the Geological Disposal Technology Working Group (hereafter “WG”) stated that safe geological disposal has to be established by field investigations, in which site suitability is confirmed in steps that show conformity with laws and regulations. The resulting Nationwide Map of Scientific Features for Geological Disposal (hereafter “Nationwide Map”) was then developed based on specific requirements and criteria [110]. In response, NUMO reviewed the processes for implementing the LS of volunteer sites [111].

In this section, based on input from the WG together with documents related to the LS stage prepared by NUMO [111], the technical processes[4] for site investigations in the stages of LS, PI and DI defined by the Final Disposal Act are described. Figure 3.2-3 shows the overall work flow for the LS and PI stages, reflecting the basic concept and procedure described in Section 3.2.1.

[4] This section describes only the processes for the site investigations from a technical perspective.

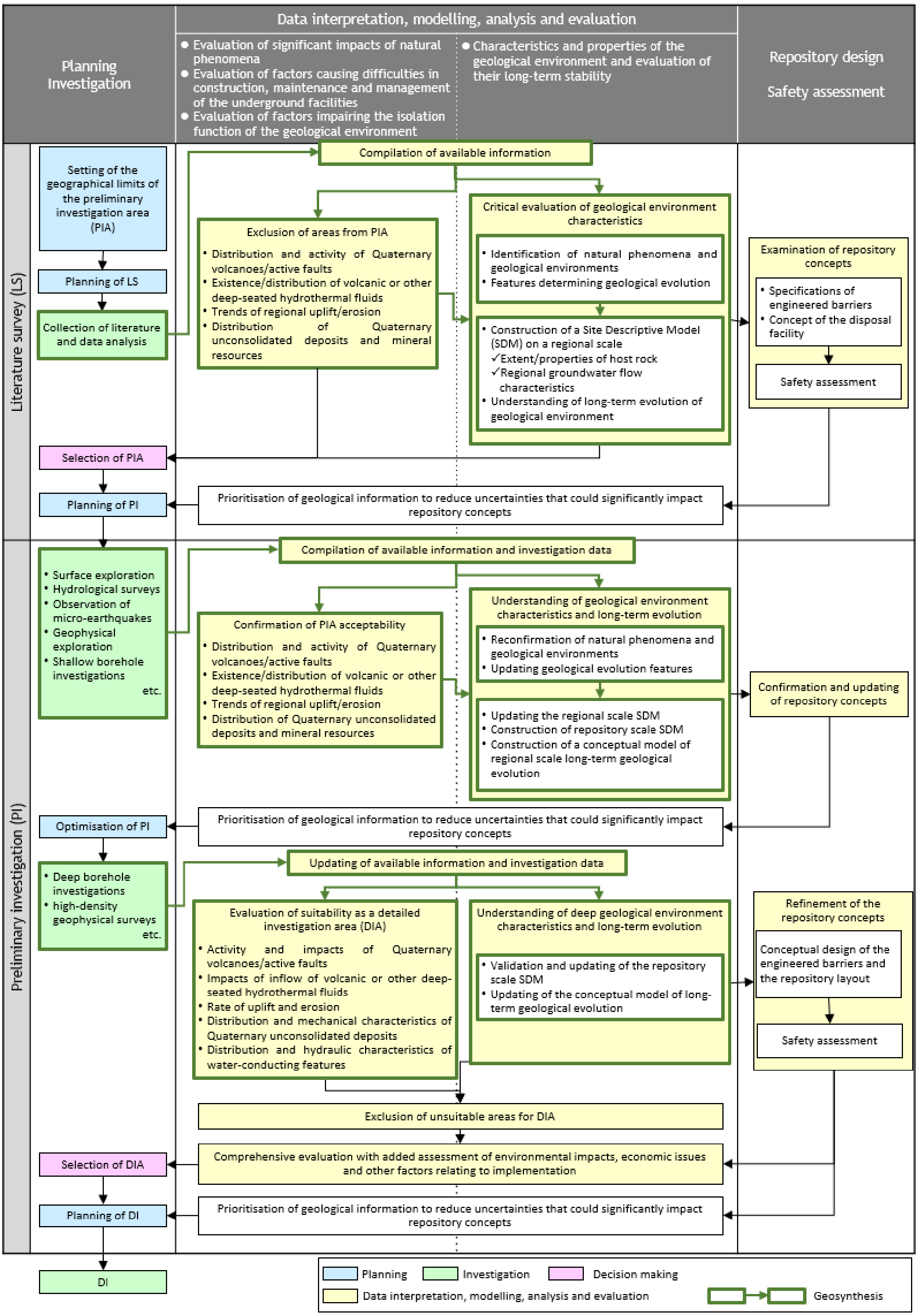

Figure 3.2-3 Workflow for LS and PI stages

(1) Literature survey stage

In the LS stage, literature information is collected based on statutory requirements and requirements/criteria related to the presentation of the scientific characteristics of the volunteer sites and their surroundings. The information collected includes publications (such as geological maps), scientific papers and research reports, which need to be checked in terms of quality and reliability and managed using appropriate systems [109]. The eligibility of application areas is assessed based on review of the collected information, with a focus on identifying the likelihood and extent of potential impact of natural perturbations in order to exclude areas that are obviously ineligible. In addition, an assessment of the distribution of unconsolidated Quaternary sediments and the presence of mineral resources is conducted; again, areas that are clearly ineligible are excluded. When factors are difficult to evaluate based on literature information, the necessity of exclusion will be judged after the subsequent PI stage.

For areas where eligibility to proceed to the PI stage is confirmed, the regional-scale SDM is refined and long-term changes in geological characteristics are evaluated. From the viewpoint of confirming the engineering feasibility of the repository and its long-term post-closure safety, the geological characteristics in Table 3.2-1 are investigated and evaluated, along with their potential evolution. A preliminary study is conducted on the specifications of the engineered barriers, the concept of the disposal facility, and the post-closure safety of the repository. With prioritisation of geological information to reduce uncertainties that could have a significant effect on the repository concept, a PI implementation plan[5] is formulated based on the geological investigation and evaluation planning manual [91].

(i) Exclusion of areas significantly impacted by natural perturbations

(a) Volcanic and igneous activity

Based on the literature information, the risk of volcanic activity in the coming tens of thousands of years results in exclusion of areas within a radius of 15 km from the centre of Quaternary volcanoes as well as areas of calderas larger than 15 km with Quaternary volcanic activity [1] [2]. Additionally, the activity history of Quaternary volcanoes, with consideration of temporal and spatial changes related to the history of geological structure development, will be evaluated. Further areas clearly identified as likely to have magma intrusions and/or eruptions at the surface over the next tens of thousands of years are also excluded.

Thus, areas that are clearly expected to have a significant risk of such impacts can be excluded. However, if volcanic rocks (eruptive or intrusive) or volcanic terrain with an unclear age are found in the vicinity, it may not be possible to make an appropriate judgement. The uncertainties resulting from this are examined in detail in the PI stage.

(b) Migration and inflow of volcanic hydrothermal and deep-seated fluids

Extending from the assessment above, the relationship between underground structures and the location of magmatic activity is assessed. If significant effects from geothermal activity are expected, such as hot water convection due to magma or hot rock, the area involved is excluded [1] [2]. When the presence of high-temperature, low-pH or high

[5] It is possible that part of the PI implementation plan is formulated in the PI stage.

carbonate concentration water is confirmed or is likely in the future, areas where impacts are considered to be significant will be excluded [1] [2].

If the formation and age of alteration zones due to geothermal activity are unknown, or when there is little literature information on deep-seated fluids, these factors are examined after obtaining detailed data in the PI stage.

(c) Earthquake and fault activity

Literature information for both land and coastal sea areas allows exclusion of those with known faults with a large displacement that have been repeatedly active in recent geological times [1] [2]. The fault influenced zone is conservatively defined as about 1% of the fault length, based on the literature data that gives values of about 1/350 to 1/150 of the fault length [112]. On the basis of a more detailed evaluation of earthquake and fault activity, the following areas are excluded (Figure 3.2-4): (1) areas included in damaged zones outside main fault zones, (2) areas with evident large folds and flexures that continue to be active, (3) areas where there is a clear probability that new deformation may occur due to the activity of the underlying fault structures [1] [2].

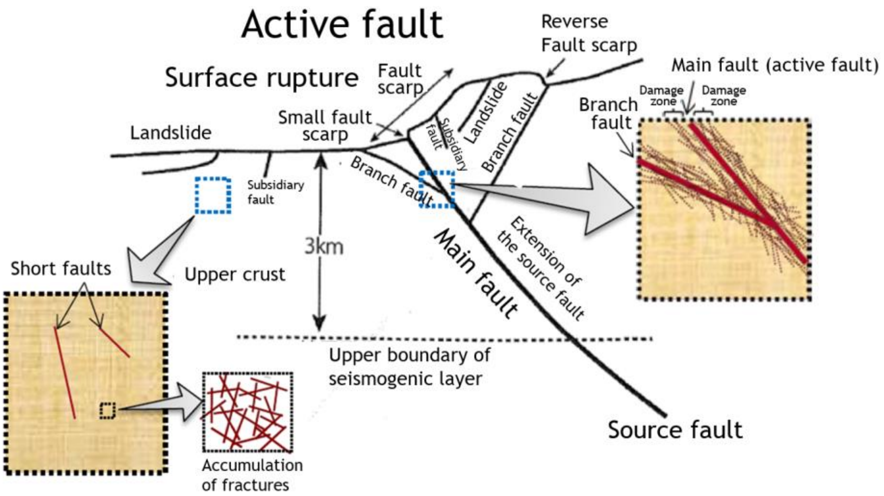

Figure 3.2-4 Influence of fault activity (Modified from Advisory Committee for Natural Resources and Energy, 2017 [2])

In the evaluation, a proper judgement cannot be made for faults with a small displacement, faults with unknown activity history, or faults with surface signatures but unknown underground structure. These are examined in detail in the PI stage.

(d) Uplift/erosion

Based on literature data, areas where the determined erosion in the last 100 ky exceeds 300 m are excluded [1] [2]. Additionally, areas such as inland mountains where uplift is expected to exceed 300 m over the next 100 ky, and coastal areas where erosion is expected to exceed 300 m over the next 100 ky are excluded. This is determined either by an equivalent uplift rate in inland mountainous areas or a combination of such uplift with the impact of expected future erosion in coastal areas.

In cases where there is more than one interpretation for the age of the topographic surfaces used for calculating uplift, or where the uplift estimated by multiple methods differs, more information is collected and evaluated in the PI stage.

(ii) Exclusion of areas with unconsolidated Quaternary sediments and mineral resources

Areas are excluded as outlined in Section 3.1.2 (2) if unconsolidated Quaternary sediments are present at depths of 300 m or more. In addition, areas are also excluded if mineral resources with significant economic value exist [2].

If the literature information is inconclusive, or cases where materials present are not currently considered as mineral resources but could be considered valuable in the future (such as geothermal/hot springs and groundwater resources), these factors are examined further in the PI stage.

(iii) Evaluation of geological environment characteristics and their long-term evolution

Based on comprehensive interpretation of literature information, geological characteristics of the volunteer areas are determined. From an understanding of the spatial distribution and geometry of formations and rock bodies, together with their hydraulic/mechanical characteristics, a regional-scale SDM that visualises these factors is constructed. As stated in Section 2.4.4, because it is important to consider groundwater migration scenarios when assessing post-closure safety of the repository, groundwater recharge and runoff areas will be determined and the regional groundwater flow field evaluated. This, together with an assessment of potential impacts of natural perturbations, allows extrapolation to determine future evolution of key characteristics, such as hydraulic and chemical conditions, using paleo-hydrogeological techniques [61] [87], together with evidence of long-term stability in similar geological environments [113].

In the LS stage, it is likely that sufficient information on the geological environment cannot be obtained and the resultant SDMs and their assumed evolution involve large uncertainties. By assigning priority to geological information that will reduce uncertainties relevant to the repository concept and associated safety case, the required supporting information can be obtained during the PI stage.

(2) Preliminary investigation stage

During the PI stage, according to the investigation plan formulated during the LS stage, a series of systematic investigations is conducted for the site and surrounding areas, aimed to confirm LS conclusions regarding site eligibility. Based on the information obtained, the spatial distribution of key characteristics and their long-term evolution are captured within models at regional and repository scales. Further information on geothermal/hot springs, earthquakes, ground deformation/displacement and pyroclastic flows acquired at this stage (corresponding to influencing factors (2) - (4) in Table 3.1-1), allows the extent of potential perturbation impacts to be examined, as well as possible countermeasures to reduce or avoid their impacts (for further details, see Sections 4.5 and 4.6).

The PI stage involves stepwise implementation in multiple phases to ensure that the priority geological information specified during the LS stage can be obtained reliably and efficiently [91] [109]. An example of the implementation protocol for such PI is presented below, but may be modified depending on the specifics of the site as found during the LS.

Preliminary regional investigations at the volunteer site include surface exploration, hydrological surveys, observation of crustal deformation and microearthquakes, together with geophysical exploration from the air, ground and sea surface. If necessary, relatively shallow borehole investigations (up to a depth of several hundred metres) can be included (e.g. borehole drilling, physical/fluid logging, hydraulic/mechanical tests, and laboratory tests of cores). Supplementary investigations may also be conducted in surrounding areas to understand the regional effects of natural perturbations and the development history of regional geological structures [1] [2] [22].

Based on the results of such initial investigations, LS conclusions with regard to the eligibility of a volunteer site may be confirmed. Within the preliminary investigation areas (PIAs), the potential for significant future impacts from natural perturbations is assessed in the light of the limitations of the investigation and evaluation techniques available. After reconfirming the geological characteristics and processes to be considered, the regional-scale SDM from the LS is updated, and a more detailed repository-scale SDM is constructed based on it. A long-term conceptual model of geological evolution is then refined from the expanded knowledge base and priority information is identified to reduce key uncertainties in these models. This leads to a review of the preliminary investigation plan to optimise direct investigation of the deep underground environment as described next.

Deep subsurface investigations (phase 2 of the PI stage) include borehole investigations and high-density geophysical surveys targeting depths of 1,000 m or more, thus obtaining information that cannot be derived via surface investigations. The locations and depths of the boreholes to be drilled are determined based on the results of the preliminary repository concept, updated based on the SDMs noted above. From these results, and with consideration of statutory requirements for the selection of detailed investigation areas (DIAs), NUMO will evaluate the range of influence and possible future impacts of natural perturbations on the repository, associated tunnel excavations (e.g. distribution of unconsolidated sediments or rocks with insufficient mechanical strength) and the safety functions of a repository (e.g. water-conducting features, risks of significant groundwater flow and/or associated chemical disturbances). Areas that are clearly poorly qualified (based on results of evaluation of the repository safety functions) are excluded. The SDM representations on regional and repository scales are refined and the conceptual model of long-term geological evolution at a regional scale is improved.

From the PIAs (or options within a PIA), those that are more appropriate from the viewpoint of being a candidate (or prospective) repository site are selected. Included in the consideration of candidate sites are the ease with which further site characterisation and construction can be carried out, whilst also minimising environmental impacts. For the target host rock formations, understanding of their spatial distribution (depth and extent), geological characteristics and long-term evolution is captured within the repository-scale SDM. Suitability is then evaluated by taking into account also the efficiency and economic aspects of required detailed investigations. For potential host rocks, the depth at which the repository can be constructed and the resulting available area are determined (for details, see Sections 4.3 and 4.5.4 (1)).

The detailed investigations are again planned with a focus on geo-environmental information that should be acquired with priority in order to reduce uncertainties that have a large impact on the design of the engineered barriers and repository layout, as well as the results of the safety assessment. In addition to a repository design and construction plan aimed at reducing the environmental disturbance due to the construction and operation of the repository, a monitoring plan will be produced in order to determine the baseline conditions used for safety assessment, as described in Section 2.3.3 (3).

(i) Exclusion of areas where effects of natural perturbations are significant

(a) Volcanic and igneous activity

Based on newly acquired geo-environmental information, the evaluation results from the LS stage can be confirmed, ensuring that areas where significant impacts of natural phenomena are expected to occur in the future, are excluded [2].

Specifically, in the PIA and its surroundings, information from surface exploration, geochemical analyses of surface springs, and geological/geochemical investigations using boreholes is synthesised to determine the presence or absence of indications of volcanic activity and, in particular, high temperature anomalies that may indicate hidden magma chambers. Surface exploration, geological analyses (such as radiometric dating and chemical analysis of volcanic rocks), and geophysical surveys such as airborne/terrestrial electromagnetic surveys and microearthquake observations are combined to obtain information on the extent and frequency of volcanic and igneous activity over the Quaternary and any associated potential for future magma chamber formation.

(b) Migration and inflow of volcanic hydrothermal and deep-seated fluids

The expanded knowledge base will allow confirmation of exclusion of areas where significant thermal or chemical effects from inflow of volcanic hydrothermal and/or deep-seated fluids are expected in the future [2].

Specifically, investigations will target information on geological structures that can potentially form flow paths for such fluids, the temperature distribution of deep waters, and the spatial variation of groundwater chemistry. Together with the assessment of volcanic activity described above, the existence and distribution of hydrothermal fluids and their range of influence are evaluated.

(c) Earthquake and fault activity

The PI stage extends knowledge on the area of influence of faults with repeated activity and large displacements, the area of their associated deformation zones, the presence of active folds and flexures, to assure that areas likely to be significantly affected by such activity in the future are excluded [2]. In particular, this confirms that faults and folds that have undergone significant deformation in the Quaternary are unlikely to have significant effects in the future.

Specifically, surface fault exploration, terrace topographical surveys, micro-topographical surveys, geophysical surveys, borehole investigations, and radiometric dating of materials in fault and fault zones are conducted. This provides information on the presence or absence of evidence of fault activity, the width of any faults and/or fault zones, relevant geological structures at depth, the history of fault activity in the Quaternary, the structure of folds and flexures and their activity pattern, and the deformation mode of relevant formations. Through synthesis of this information, the understanding of the range of influence of such features is improved. The probability that faults are concealed underground, that faults branch (see Figure 3.2-4) and extend further, and that new fault displacement occurs in the vicinity of existing faults, will also be investigated. Based on these results, it is possible to determine areas where such activity occurs and where their effects, such as regional deformation or fault movement, are likely to be significant, making engineering counter-measures difficult.

Although activity in recent geological times may be unknown in some cases, the possible effects of future displacements of formations and expansions of fault zones is evaluated for those where the possibility of activity cannot be ruled out, assessing possible impacts on key safety functions. For places where strata and rock bodies with quite different properties are in contact with each other on a large scale, such as the edges of sedimentary basins, based on information from regions with similar conditions, areas are identified where future displacements may have significant effects on safety functions environment. This includes taking into account the onset of future fault activity and the possibility of fault activity that is in the opposite direction to the present (inversion tectonics).

(d) Uplift/erosion

The PI stage will confirm that areas are exclude if a significant impact over relevant timescales is likely for the expected repository depth [2].

Specifically, topographic surveys, geological exploration, geophysical surveys and borehole investigations are carried out. These include assessments of: the distributions and formation ages of terraces and eroded surfaces, sediment distributions; depths, formation ages and shapes of dissected valleys and riverbed slopes. Through comprehensive interpretation of this information, future uplift and associated erosion, considering climate and sea-level fluctuations, is estimated. In particular, the extent and distribution of erosion in the future is estimated based on consideration of contributions from general denudation, lateral and vertical erosion by rivers (including consequences of river capture) and sea erosion in coastal areas. The specific impacts of uplift/incision of rivers due to sea-level change, glaciation, and permafrost in the past several hundred thousand years is also considered. As background, it is important to evaluate long-term crustal movements determined from geological observations and relate these to short-term crustal movements as observed geodetically.

(ii) Exclusion of areas with unconsolidated Quaternary sediments and mineral resources

The PI stage will extend investigations of distribution of unconsolidated Quaternary sediments at the assumed repository depth, as well as for the existence of mineral resources of high economic value and, if they exist, these areas are excluded as described in Section 3.1.2 (2) [2].

(iii) Evaluation of geological environment characteristics and their long-term changes

During the preliminary regional investigations, information on the distribution and geometry of strata and rock bodies, faults and fracture zones at or near the surface, as well as their thermal and mechanical properties, is obtained mainly by surface mapping, geophysical surveys from the air/ground/sea, trench surveys, surface hydrological investigations, and shallow borehole investigations. Groundwater recharge and runoff areas are identified, together with information related to surface hydraulics and geochemical properties of the surface waters and shallow groundwater.

During the subsequent investigations, information in three dimensions from deep boreholes can be obtained. The information obtained includes: structural geology (faults/fractures, folds, facies distribution, etc.), rock thermal and mechanical properties (thermal conductivity and mechanical strength, etc.), hydraulic properties and solute transport/retardation characteristics of strata/rock bodies/faults and fractures and the geochemistry of groundwater. Through a comprehensive interpretation of the acquired information, the extent of geological formations and rock bodies with favourable characteristics is confirmed from the viewpoint of tunnel excavation and radionuclide containment. By obtaining paleohydrogeological evidence (e.g. isotope ratios, crystal structures of fracture-filling minerals) from groundwater, rocks and minerals, the long-term evolution of the hydro-geochemical environment is evaluated.

(3) Detailed investigation stage

During the detailed investigation (DI) stage, a series of systematic investigations are carried out in two phases; the first phase from the ground surface and the second phase within a special underground investigation facility (UIF) [109].

During the surface investigations, which may be carried out at one or more detailed investigation areas (DIAs) and/or a number of sites within these DIAs, information on the geological environment around the proposed repository site is acquired according to an Investigation Plan (IP) formulated during the PI stage. Based on this newly acquired information, the regional- and repository-scale representation of the SDMs and the conceptual model of long-term evolution are re-assessed and updated. To understand in detail the hydraulic and mechanical characteristics of representative host rock(s) and the nuclide migration and retardation characteristics of any water-conducting features, smaller scale representations of the SDMs are constructed that focus on the size of disposal panels and also the water-conducting microstructure of faults and fractures. Furthermore, geological information to reduce the uncertainty of parameters that have a high impact on these models is prioritised. Specific items to be considered in further studies within the UIF is then determined, together with the required level of detail of such investigations.

For the second phase of DI, a UIF is constructed in a suitable area of the selected host rock and investigations conducted to understand in more detail the underground geological characteristics and the temporal and spatial changes associated with this construction [114]. Existing experience and technology from domestic and overseas URLs can be extended as needed. Based on results obtained, in the light of the statutory requirements for selecting the site for a final repository, confirmation that the chosen host rock has favourable geological characteristics from the viewpoint of waste confinement is is obtained. The SDMs, including the conceptual model of long-term evolution, will be refined to build confidence that the favourable geo-environmental properties of host rock are maintained for a sufficiently long time. From associated assessment of operational and post-closure safety, the selected layout of the repository and the location of surface facilities are confirmed as meeting requirements.

It is assumed that areas with significant risks of future natural perturbations have been avoided based on PI studies. During investigations conducted in the UIF, however, there may indications of perturbations that need to be reconsidered. When these are encountered, the probability of them having significant impacts will be examined, taking into account the limitations of applicable investigation and evaluation technologies.

(i) Assessing the potential of significant effects of natural perturbations

(a) Volcanic and igneous activity

When encountering intrusive rocks such as dikes or large-scale alteration zones, their formation age is estimated by dating constituent minerals, which complements detailed geological assessments of their occurrence. The rock temperature gradient/spatial distribution, and dissolved gas in groundwater are investigated in detail to understand the relationship between intrusive rocks, alteration zones and associated magmatic activity.

(b) Migration and inflow of hydrothermal fluids

When groundwater with high temperature, low pH or high carbonate concentration is observed, its origin and source contributions from volcanic hydrothermal or deep-seated fluids are identified based on chemical and isotopic data (e.g. Li/Cl, $^{3}He/^{4}He$, etc.). Based on information on geothermal conditions, resistivity, microearthquake occurrence, etc., the potential extent of groundwater migration and associated inflow routes to locations where the repository will be constructed is investigated.

(c) Fault activity

When encountering large-scale faults or fault zones, the probability of these extending from the surface to relevant depths is evaluated, taking into account the geological information from surface investigations. Radiometric dating of minerals in the fault zone, as well as mineralogical and chemical/isotopic analyses, are conducted to determine if these were formed as a result of repeated activity in the Quaternary and the probability that a fault might be reactivated.

(ii) Evaluation of geological environment characteristics and their long-term changes

Based on investigations from both phases, more detailed information on the representative host rock setting is obtained. In addition to detailed characterisation within the UIF itself, in-situ tests using shafts and tunnels excavated to construct it are conducted. The spatial distribution of geological structures (faults, fractures, lithology, etc.), thermal/mechanical/hydraulic properties of all relevant rocks, nuclide migration/retardation properties of water-conducting features (fractures, water-conducting microstructures, etc.), geochemical properties of groundwater, as well as changes in the geological environment due to this construction, are investigated in detail. From a synthesis of this information, areas with favourable geological characteristics from the viewpoints of repository construction, operation and assured post-closure performance are identified. Extending the PI knowledge base, information such as paleohydrogeological evidence from groundwater/rocks and minerals to gain understanding of long-term site evolution is obtained.

3.2.3 Site characterisation technology

Stepwise site-specific geological investigations are conducted according to the procedures described in Section 3.2.2, based on the best technology available. In addition to assuring efficiency and cost-effectiveness of site investigation, for each study item listed in Table 3.2-1, it is necessary that these technologies enable information to be acquired with the required level of quality.

Based on these requirements, NUMO has summarised the status of relevant technology development, testing and improvement by relevant research organisations, with a focus on needs for PI and DI investigations (e.g. Ota et al. 2007 [74]; Saegusa et al. 2007 [92]; JAEA, 2010 [115]; 2013 [105]; 2015 [116]; 2018 [117]; CRIEPI, 2013 [118]; 2013 [119]; 2013 [120]; 2018 [121]; 2018 [122]; AIST, 2013 [67]; 2013 [123]; 2016 [124]; AIST/JAE/RWMC/CRIEPI, 2016 [68]; 2017 [69]; 2018 [125]). In particular, from the viewpoint of accurate characterisation of relevant environments, the objectives, methods, application examples, effectiveness and technical issues for individual technologies have been summarised in Supporting Report 3-11. In the future, NUMO will work with, and coordinate roles of, relevant national research institutions in order to systematically develop required technologies prior to the start of each siting stage (described in detail in Section 3.5.2). In parallel, as described in Section 3.2.2 (3), based on experience in domestic and overseas URLs, the applicability of associated technologies for the UIF will be assessed and refined as required, to resolve any technical issues identified as site investigation progresses.

In the next section, development of relevant research and evaluation technologies since the H12 report is overviewed. In addition, the probabilistic evaluation of the occurrence and consequences of future natural perturbations on a timescale exceeding 100 ky is described.

(1) Development of investigation and evaluation technologies

Since the H12 report, and particularly since 2004, R&D roadmaps and five-year overall plans have been formulated through coordination meetings with the Agency for Natural Resources and Energy (ANRE) and relevant research institutions [126] [127] [128] [129] [130]. The following sections overview the current status of both technology to better assess the potential impacts of natural perturbations and that for characterising geological environments together with their long-term evolution.

(i) Technology related to the impacts of natural perturbations

Investigation and evaluation technologies for the PI stage, aimed at understanding past and future occurrence of natural perturbations and their associated effects, especially for inland applications, are being further developed and assessed via case studies [115] [116] [131].

Specifically, technologies are being developed for determination of:

- The existence and spatial distribution of deep underground faults and magma chambers, using a combination of geophysical and geochemical methods [16] [132] [133].
- Active faults that are difficult to identify at the surface using airborne laser measurements (that dramatically improve detection under dense vegetation) and use of geochemical indicators to confirm the presence of deep-seated fluids [133] [134] [135].
- The activity of faults based on mineral shapes and radiometric age for infill within fault zones [136] [137].
- Uplift and erosion rates using river terraces and thermochronological methods [138] [139] [140] [141].

Extending from coastal land to offshore areas, AIST, JAEA and CRIEPI are developing technologies for assessing uplift and erosion [68] [69] [125], improving investigation techniques to confirm the presence of magma and associated fluids, extrapolating land uplift and erosion patterns to offshore areas and improving terrace evaluation and chronology methods using empirical indicators [142].

For quantifying the probability of future natural perturbations and associated changes in geological environment characteristics, the following topics are being promoted:

- Development of long-term prediction models for occurrence of new volcanoes and faults [143] [144].
- Evaluation methodology for changes in the groundwater flow systems due to fault movements [145].
- Simulation methodology for topographic changes up to about 100 ky in the future [140].
- Groundwater flow analysis considering topographic changes and climate perturbations [146] [147].

For time periods exceeding 1 My, a model capable of simulating the long-term changes of the geological environment in three dimensions has been constructed. In addition to the visualisation/numerical techniques and uncertainty evaluation methods required, development of fundamental technologies for establishing the geological database for model construction and validation is also in progress [117].

Furthermore, utilising the latest analytical methods for trace elements and isotopes, JAEA and CRIEPI have been pursuing improvements in the technology for accurately ascertaining past occurrence times of volcanic/igneous activity and fault movements, the rate of uplift and erosion, the age of formation of strata/rock bodies/minerals and the residence time of groundwater [75] [120] [125] [133] [148] [149] [150] [151] [152] [153] [154] [155]. This is essential to support arguments for the long-term stability of relevant geological environments.

(ii) Investigation and evaluation methodology for geological characteristics and their long-term evolution

JAEA's work at the Horonobe and Mizunami URLs forms the core of this R&D programme. In these facilities, initial investigations from the ground surface followed by studies at the time of their excavation, corresponds to site characterisation PI and DI stages.

As described in Section 3.2.1, this resulted in uncertainty reduction in an iterative manner and coordination of engineering design and safety assessment through integration of geological environment information. This work established the effectiveness of fundamental technologies for staged site investigations of both Neogene sedimentary rocks and granitic rocks (which represent plutonic rocks) for near-coast areas [61] [74] [85] [87] [92] [105]. Essential knowhow and the basis for judgments related to site assessment have been compiled to serve as a knowledge base for investigation/evaluation technologies, as well as improving their practicality and reliability [105] [115] [116].

In parallel with such work, a R&D programme led by AIST and CRIEPI is being conducted for coastal areas for which relatively little site investigation experience is available. This includes the following topics:

- Interpretation and modelling of geological structures based on literature information [123].
- Geophysical exploration from land to sea and assessment of the spatial distribution of freshwater/saltwater mixing areas [67] [124].
- Exploration of groundwater seepage into the sea floor [156].
- Controlled directional drilling and borehole investigations [118] [122].
- Examination of technologies for drilling offshore [123] [124].

Geophysical technology to continuously profile coastal land to sea is recognised as an issue and improvements are under development, such as shown in Figure 3.2-5. As noted in Section 3.1.3, improved understanding of the origin, age, and flow of coastal groundwater has been obtained around the Horonobe URL [67] [68] [69] [75]. With the aim of development of comprehensive sub-seabed characterisation technologies for coastal areas, R&D is ongoing on [68] [69] [123] [124]:

- Geological structure.
- Determination of regional groundwater flow.
- Relationship between faults and groundwater flow.
- Information on long-term changes in groundwater flow that can be obtained by borehole investigations.

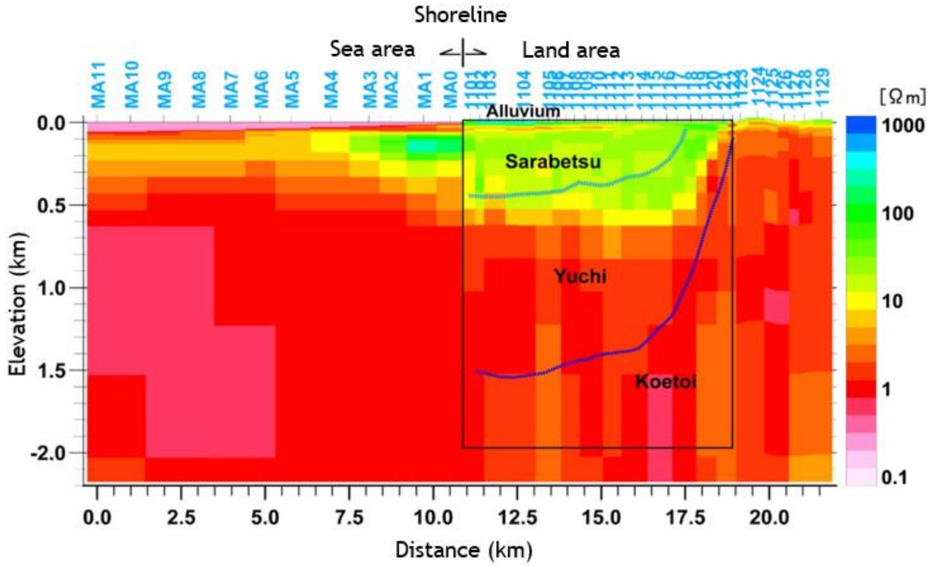

Figure 3.2-5 Modelled distribution of subsurface resistivity based on a sea-land electromagnetic survey in the Horonobe area, Hokkaido (Modified from AIST, 2013 [67])

For sedimentary rocks that make up the accretionary prisms widely distributed in coastal areas, and for Neogene sedimentary rocks, NUMO working with CRIEPI to confirm the effectiveness of systematic investigation/evaluation technologies developed by research institutions (for example, drilling technologies and borehole investigations), so that these will be applicable in the PI stage [109] [157] [158]. Through this initiative, it is aimed to accumulate the technical knowledge and practical experience to implement required investigations efficiently and effectively.

Based on the current state of technology development for coastal areas, a study group for technical issues related to geological disposal beneath the coastal seafloor pointed out that, although it is necessary in the future to advance specific technologies through verification of their applicability, it is possible to conduct stepwise geological investigations in coastal areas by combining relevant technologies for land areas (inland and coastal areas) [159].

For the technologies required in the latter half of the DI stage, based on experience in JAEA's URLs, the following may be considered:

- Evaluation of the function of faults encountered in tunnels as water-conducting features (e.g. relationship to repeated fault movement and formation of infill minerals) [160].
- Investigation and evaluation of water-conducting microstructures (e.g. the geometry and connectivity of the pores that impact the migration and retardation of radionuclides) [121].
- Demonstration of techniques for assessing changes in the groundwater flow field and water chemistry due to tunnel excavation and damage to rock around the tunnel [161].
- Development of technology to examine the long-term behaviour of rock around the tunnel after backfilling.
- Long-term monitoring of groundwater pressure and chemistry [162].

The current status of the technologies noted above, particularly considering PI implementation, is summarised according to the topics previously listed in Table 3.2-1 and presented in Table 3.2-2 (those related to the effects of natural perturbations) and Table 3.2-3 (those related to the geological environment characteristics and their long-term evolution). The aim will be to resolve most of the issues described in these tables during the PI stage (see Section 3.5.2). Details of the investigation and evaluation technologies are provided in Supporting Reports 3-6 and 3-9, with Supporting Report 3-11 comprehensively summarising details of the individual methodologies.

Table 3.2-2 Current status of investigation and evaluation technologies related to the effects of natural phenomena (1/2)

Site investigation/evaluation techniques		**Current status** • **Proven technology** • **Available characterisation techniques and their applications**	**Issues** • **Methodology to be developed and refined** • **Knowledge to be developed and refined**
Volcanic and igneous activity	Probability and extent of magma migration from Quaternary volcanoes	• Geological characterisation of magma activity, and history of development • Geophysical and geochemical characterisations of deep underground structure of volcanic bodies • Confirmation of the existence of magma chambers for inland areas using geophysical survey	• Methods for confirmation of the existence of coastal sea area magma chambers • Magma activity ranges according to activity types, such as stratovolcano and caldera
	Probability and extent of new volcanic (magma-supplying) occurrences	• Geological characterisation of the temporal and spatial evolution of volcanic activity • Geophysical and geochemical characterisation, including seismic velocity and thermal structures underground • Model of the uneven distribution of high temperature areas in the crust and mantle	• Confidence of model related to time changes and continuity of high temperature areas in the crust and mantle
Movement and inflow of volcanic hydrothermal and deep-seated fluids	Extent and scale of future thermal and chemical impacts of hydrothermal deep-seated fluids	• Characterisation of effects of T-H-C conditions of volcanic hydrothermal fluids *(The technologies developed in the field of geothermal resources can be applied)* • Geophysical characterisation of the existence of deep-seated fluids and related geological structures for inland areas	• Distribution of deep-seated fluids, along with chemical/isotopic composition, determination methodology and relationships to faults/tectonic structures • Method for confirmation of the existence of deep-seated fluids for coastal sea areas • Comprehensive technologies for characterisation of distribution and flow paths of deep-seated fluid, together with potential impacts

Table 3.2-2 Current status of investigation and evaluation technologies related to the effects of natural phenomena (2/2)

Site investigation/evaluation techniques		Current status • Proven technology • Available characterisation techniques and their applications	Issues • Methodology to be developed and refined • Knowledge to be developed and refined
Earthquake and fault activity	Distribution of active faults and their present and future activity	• Methods such as topographic interpretation, geodetic observation, surface geological survey, trench survey, geophysical survey, borehole investigation for inland areas • Detection of active faults after large earthquakes occurring in areas where active faults are unconfirmed on the surface, using a combination of the above techniques • Methods such as seabed topography surveys and seismic surveys for coastal sea areas • Model experiments and numerical analyses on the branching and extension of active faults and on the reactivation of faults	• Improvement of resolution of methods such as seabed topography surveys and seismic surveys for coastal sea areas • Comprehensive technologies for characterisation of active faults distributed around shorelines, based on the developed investigation methods for inland areas and coastal sea areas • Characterisation of distribution and activity of topographically obscure active faults based on geochemical methods, and accumulation of the case • Characterisation of the activity of faults in the absence of overlying strata, based on mineralogical investigation and dating techniques for materials in fault zones, and accumulation of the case
	Extent of hydraulic and mechanical effects associated with fault movements	• Width, distribution and properties of fault zones and process zones, their effects on hydrology and mass transport, and changes with time	• Characterisation of the extent of the influence of active faults, and accumulation of the case
	Changes in the geological environment associated with earthquake activity	• Acquisition of the knowledge to support claim that water pressure changes associated with large earthquake are small and temporary • Characterisation of water pressure changes associated with large earthquakes using volumetric strain analysis of the crust	• Outflow of hot spring associated with the Tohoku earthquake and recovery of hydraulic conductivity of faults associated with earthquakes
Uplift and erosion	Rate of future uplift and subsidence Future erosion rate and landform change	• Comprehensive technologies for characterisation of rate of uplift and erosion	• Characterisation methods for inland areas where effective indicators of uplift and erosion have not been developed • Characterisation methods for coastal sea areas
	Climate and sea-level change	• Comprehensive technologies for characterisation of global climate and sea-level change • Individual technologies for assessing regional climate change	
Methodology for assessing the likelihood of natural perturbing phenomena* occurring over a long period of time, e.g. >100 ky in the future		• Evaluation of the probability of future perturbations by extrapolation based on the assumption of uniform continuity of crustal movement • Regional characteristics of future perturbations in the scientifically predictable period	• Probability of future natural perturbations • Regional characteristics and temporal/spatial changes in the occurrence/variation of such perturbations • Methods of classification of perturbations for development of safety assessment scenarios, and assessment of associated probability and uncertainties

* Encompasses volcanism and igneous activity, the movement and inflow of volcanic hydrothermal and deep-seated fluids, earthquake and fault activity, and uplift and erosion.

Table 3.2-3 Current status of investigation and evaluation technologies for geological environment characteristics and their long-term changes (1/3)

Characteristics to be understood		Current status • Proven technology • Available characterisation techniques and their applications	Issues • Methodology to be developed and refined • Knowledge to be developed and refined
Geological structure	Spatial distribution and geometry of groundwater flow paths Spatial distribution and geometry of geological strata and rock bodies Spatial distribution of lithologies and fractures within geological strata and rock bodies	• Comprehensive method combining geophysical surveys, borehole investigations and tunnel mapping for inland areas • 3D geophysical survey for the characterisation of spatial distribution of faults *(including technology developed in the field of resource exploration)* • Geophysical survey methods for faults distributed near the shoreline • Geological characterisation for coastal sea areas *(including technology developed in the field of resource exploration and academic research)* • Characterisation of the connectivity of faults and water-conducting fractures at the repository scale • Borehole drilling and investigations • Detection of microstructures • Development of geological models at various spatial scales	• Available information on 3D geophysical surveys • Improvement of data analysis methods for nearshore geophysical surveys • Test applicability of site investigation technology for coastal sea areas • Technology for comprehensive characterisation of the connectivity of faults and water-conducting fractures. • Borehole drilling and investigation technologies for rock masses including weaker layers • Improvement in accuracy of microstructure detection in boreholes by mud drilling and boreholes drilled from tunnels
	Geometry of water-conducting microstructures that contribute to nuclide migration and retardation	• Characterisation of the geometry of water-conducting microstructures using in-situ tracer tests and laboratory tests • Knowledge on conceptual modelling of water-conducting microstructures for Neogene sediments and granite rock	• Methods for estimating the aperture of water-conducting microstructures using high-viscous fluids and radon concentrations • Information for conceptual modelling of water-conducting microstructures in rocks other than Neogene sediments and granite
Thermal environment	Spatial distribution of geothermal gradient Thermal properties of strata and rock bodies	• Characterisation of geothermal gradient and thermal properties of rock mass based on borehole investigations and laboratory tests • Borehole investigation methods	• Borehole investigation technology for rock masses including weaker layers

Table 3.2-3 Current status of investigation and evaluation technologies for geological environment characteristics and their long-term changes (2/3)

Characteristics to be understood		Current status • Proven technology • Available characterisation techniques and their applications	Issues • Methodology to be developed and refined • Knowledge to be developed and refined
Hydrogeological condition	Spatial distribution of hydrogeological structures Spatial distribution of advection and diffusion domains Hydrogeological and gas migration characteristics of strata, rock bodies and hydrogeological structures Spatial distribution of hydraulic head and temperature	• Hydraulic properties and hydraulic head distribution using borehole investigations in inland areas • Systematic investigation methods using boreholes • Hydrogeological characterisation for coastal sea areas based on resource exploration and academic investigations • Hydrogeological modelling and groundwater flow simulation at relevant spatial scales • Hydrogeological characterisation of water-conducting features with high transmissivity (> 10^{-8} m^2/s) • Detection and hydrogeological characterisation of water-conducting features • Characterisation of gas migration in sediments and the amount of gas inflow into tunnels	• Borehole investigation technology for rock masses, including weaker layers • Test applicability of hydrogeological investigations technologies using boreholes for coastal sea areas • Knowledge on the consistent interpretation of the results of groundwater flow simulation, the age of groundwater and the distribution of groundwater chemistry • Knowledge on the existence and formation conditions of stagnant groundwater • Methodology for hydrogeological characterisation of water-conducting features with low transmissivity (< 10^{-8} m^2/s) • Improvement of borehole hydrogeological investigations using mud drilling and boreholes drilled from tunnels
	Nuclide migration and retardation characteristics of water-conducting microstructures	• Characterisation of nuclide migration, retardation processes and sorption/diffusion using in-situ tracer tests and laboratory tests • Knowledge to support conceptual modelling of nuclide migration and retardation characteristics for Neogene sediments and granitic rock	• Knowledge on the characterisation of diffusion domain using natural stable isotopes • Knowledge to support conceptual modelling of water-conducting microstructures in rocks other than Neogene sediments and granitic rock
Rock mechanical condition	Petrophysical and rock mechanical characteristics of strata, rock bodies, faults and fractures	• Comprehensive methodology combining geophysical surveys, borehole investigations from both the surface and tunnels and tunnel mapping • Systematic investigation methodology using boreholes • Characterisation of the physical and mechanical properties of the excavation damaged zone, and associated spatial distribution • Rock mechanical modelling methodology at relevant spatial scales	• Borehole investigation technologies for rock masses, including weaker layers

Table 3.2-3 Current status of investigation and evaluation technologies for geological environment characteristics and their long-term changes (3/3)

Characteristics to be understood		Current status • Proven technology • Available characterisation techniques and their applications	Issues • Methodology to be developed and refined • Knowledge to be developed and refined
Hydrochemical condition	Spatial distribution of groundwater chemistry, isotope ratios Spatial distribution of groundwater pH and Eh values Properties and distribution of gases in strata, rock bodies and groundwater	• Comprehensive methodology for understanding groundwater chemistry, isotope ratios, pH and Eh in groundwater using borehole investigations for inland areas • Understanding of spatial distribution of high-salinity groundwater for inland areas, using electrical survey methods • Systematic investigation methods using boreholes • Hydrochemical characterisation for coastal areas, based on resource exploration and academic investigations • Methodology for hydrochemical modelling and analysis at relevant spatial scales • Characterisation of properties and distribution of gases in strata, rock bodies and groundwater	• Methodology for analysis of electrical survey data for coastal sea areas • Borehole investigation techniques in rock masses including weaker layers • Test applicability of hydrochemical investigation technologies using boreholes for coastal sea areas • Test applicability of hydrochemical characterisation techniques for site characterisation of coastal sea areas
	Chemical effects of colloids, organic matter and microorganisms Nuclide migration and retardation characteristics of water-conducting microstructures	• Methodology for sampling and analysis of colloids, organic matter and microorganisms • Characterisation of nuclide migration, retardation processes and sorption/diffusion, using in-situ and laboratory tracer tests • Knowledge to support conceptual modelling of nuclide migration and retardation characteristics for Neogene sediments and granitic rock	• Knowledge to support conceptual modelling of water-conducting microstructures for rocks other than Neogene sediments and granitic rock.
Long-term evolution of geological and environmental characteristics	Evolution of the regional stress regime Development and formation of geological structures Evolution of advection domains and their hydrogeological characteristics Formation mechanisms of groundwater chemistry and associated evolution Evolution of the petrophysical, rock mechanical and thermal characteristics of strata and rock bodies	• Characterisation of regional stress field evolution, crustal movements, evolution processes for geological structures and topographic change • Methodology for modelling and analysis of long-term topographic evolution and geological structures under simplified conditions • Methodology for modelling and analysis of long-term evolution of groundwater flow conditions • Groundwater dating methodology using multiple isotopes for inland areas • Analysis and evaluation methods for long-term evolution of the physical and mechanical properties of rock masses due to the evolution of the regional stress field and geological structures	• Methodology for modelling long-term evolution of large scale heterogeneities in both topography and the geological environment with high resolution • Knowledge to support modelling of long-term evolution of groundwater flow conditions • Knowledge to allow consistent interpretation of the results of groundwater flow simulation, groundwater ages and groundwater chemistry distribution • Knowledge supporting groundwater dating using multiple isotopes for coastal sea areas • Data to test models of long-term evolution of petrophysical and rock mechanical characteristics

(2) Evaluation of the probabilities and impacts of natural perturbation phenomena

As described in Section 3.2.1, it is essential that the impacts of perturbations which can significantly affect the future performance of the geological barrier are avoided to the extent possible. However, uncertainties accompany the assessment of future occurrences due to limitations in scientific knowledge. Such uncertainty generally increases as the evaluation period becomes longer and its treatment is important in assessing potential impacts on repository safety functions.

Methods for evaluating the occurrence and impacts of such phenomena are roughly classified as: extrapolation, analogy, numerical analysis using a phenomenological model and probability theory [163]. Extrapolations from the geological knowledge base to assess potential future perturbations may be purely empirical, based on statistical analyses, or supported by more fundamental mechanistic models (e.g. [163] [164]), but all options involve considerable uncertainties. This is particularly so when the driving forces resulting from tectonic plate movements significantly diverge from current conditions (needs to be considered at times > ≈ 100 ky).

NUMO considers that stochastic methods are particularly useful for managing such uncertainties, in line with international recommendations for similar assessments, e.g. the risk of volcanic disturbances at nuclear sites [165]. For assessment of seismic risks to US nuclear power plants and volcanic risks to the Yucca Mountain Project, several different phenomenological models and parameter combinations have been developed and a probabilistic evaluation method is applied by weighting the likelihood of occurrence using expert elicitation [166].

Based on this background, NUMO developed the ITM (International Tectonics Meeting) –TOPAZ (Tectonics of Potential Assessment Zone) method for region-/site-specific risk assessment [167] [168]. To develop models of potential changes in the regional tectonics based on plate movements, the current tectonic situation in the vicinity of the site is assessed in the context of the large-scale geological environment. This method involves (1) creating scenarios and logic trees, (2) determining confidence by soliciting expert opinion in a structured manner, and (3) evaluating the likelihood of scenario occurrence. Figure 3.2-6 shows the basic structure of the resulting logic tree.

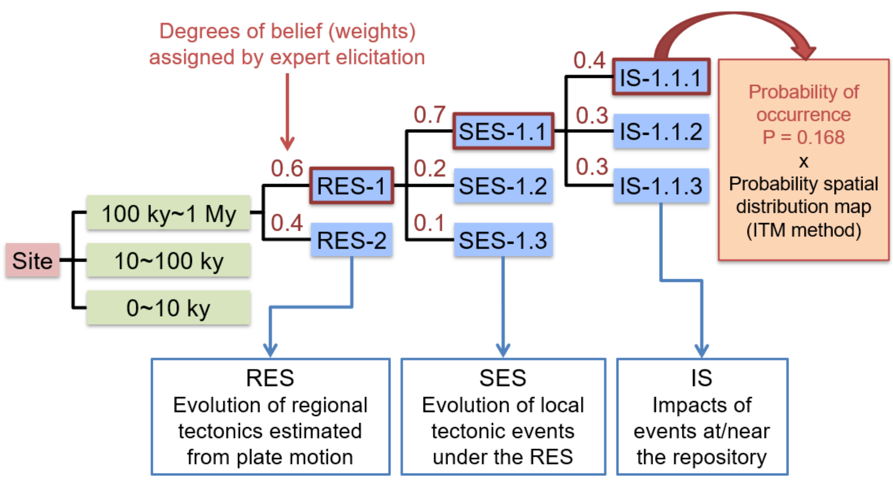

Figure 3.2-6 Information flow of the ITM-TOPAZ method and basic structure of the logic tree (Modified from Goto et al., 2014 [173])

So far, the method has been applied to volcanic/igneous activity, seismic/fault activity, and uplift/erosion, with a resolution of about 5 km × 5 km (corresponding to the repository scale) and for times up to about 1 My [169] [170] [171] [172]. After summarising the scientific knowledge necessary to evaluate the effects of such phenomena on post-closure safety, the results of the risk assessment for future volcanic and igneous activity as described in Section 3.4.1 are used for dose evaluation for the "new volcano occurrence case" in Section 6.4.3 (1).

3.3 Development of SDMs for representative host rock settings

3.3.1 Model aims and development procedure

In the staged siting process, as discussed in detail in Section 3.2.1, information obtained through investigations at the volunteer sites is synthesised into site descriptive models (SDMs), following a consistent synthesis across the many disciplines involved. The engineering practicality of repository implementation and its safety assessment based on the SDMs are then performed, with these steps repeated iteratively as siting proceeds. As no sites had come forward at the time of preparation of this report, “representative host rocks” are thus illustrated, based on the current geological knowledge base for Japan. These focus on geological formations in environments which may be eligible for site selection, having required safety functions that are expected to persist for sufficiently long time periods. A series of studies to illustrate repository design and safety assessment tailored to these settings (for details, see Chapters 4, 5 and 6) are then be conducted.

Selection and modelling of the representative host rocks proceeds according to the work flow shown as (A) to (F) in Figure 3.3-1.

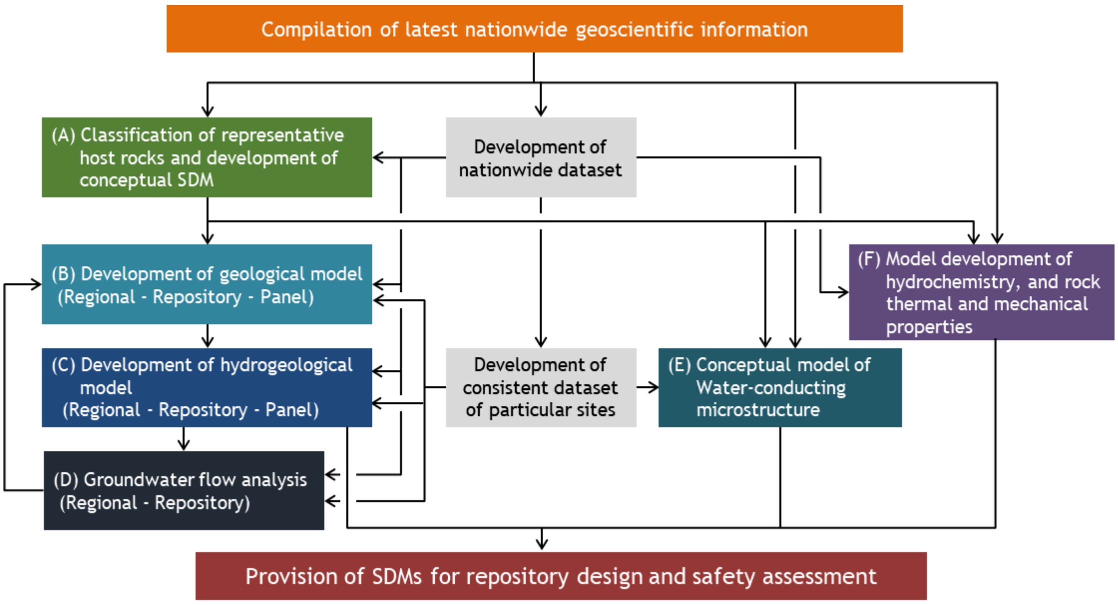

Figure 3.3-1 Stepwise procedure for developing SDMs for representative host rocks (Modified from Ota et al. 2015 [9]; Copyright (11 August, 2016) by the American Nuclear Society, La Grange Park, IL, USA)

In particular for (A), after selecting representative host rocks based on widespread distribution in Japan (Section 3.3.2), a conceptual SDM is developed for each rock type

(Section 3.3.3 (2)). Based on this conceptualisation, the (B) geological model and (C) hydrogeological model are developed (see Sections 3.3.3 (3) and (4)). In addition, based on the hydrogeological model, a groundwater flow analysis is performed (D) to determine the spatial scale of the area to be studied in more detail (see Sections 3.3.3 (3) and (4)). Taking into account that the quality and quantity of the geoscientific information obtained in each investigation stage can vary, the regional scale model mainly uses the nationwide database. In modelling from the repository scale to the panel scale, the geoscientific information for particular sites where the deep geological and hydraulic characteristics of the rock mass have been comprehensively studied is used. The SDMs are developed so that the regional, repository, and panel scale representations form a nested structure.

For the selected host rocks, based on the results of case studies in the particular sites, (E) a conceptual model of water-conducting microstructure to allow quantification of the migration and retardation of solutes is developed (see Section 3.3.3 (5)). Additionally, based on nationwide dataset, (6) hydrochemical and rock thermal/mechanical models are developed (see Sections 3.3.3 (6) and (7)). The SDMs constructed for representative host rocks are thus clearly more realistic than those used for previous safety assessments in Japan [9].

3.3.2 Classification of representative host rocks

From the viewpoint of geological disposal, seven rock groups have been identified (Section 3.1.3 (1)) and mapped (Figure 3.1-1) [26].

Quaternary sedimentary and volcanic rocks are widely distributed at the surface, but when unconsolidated below 300 m these are excluded from consideration [2]. Further, according to Yasue et al. (2014) [174], the distribution of these two rocks at reference depths of 500 m and 1,000 m, is greatly reduced compared to their distribution at the surface (approximately 6% and 1%, excluding areas within 15 km from the centre of Quaternary volcanoes, within which 80% of Quaternary volcanic rocks are found) [110]. Although eligibility as a host rock for the repository is determined through the staged site investigation process, compared to the other five rock types it is reasonable to assume that these are relatively unlikely to be representative host rocks. In this report, therefore, Quaternary sedimentary and volcanic rocks are excluded from further consideration.

For each of the other five rock types, the geoscientific information compiled in the H12 report [7] has been updated (e.g. NUMO, 2013 [8]) with a focus on characteristics important from the viewpoint of repository design and safety assessment. An overview is presented in Table 3.3-1, including thermal conductivity, uniaxial compressive strength and effective porosity, which are important from the viewpoint of repository design, as well as structures of water-conducting features, hydraulic conductivity and effective porosity, which are important from the viewpoint of safety assessment.

Excluding areas within 15 km from the centre of Quaternary volcanoes and the areas of Quaternary sedimentary and volcanic rocks, the abundance of each rock type has been calculated using the 1:200,000 Japan geological map [65], while abundance at 500 m and 1,000 m below ground level has been calculated based on Yasue et al. (2014) [174]. The geoscientific information collected and analysed for these rock types and the statistically processed data are summarised in Supporting Report 3-13.

For Neogene sedimentary rocks and plutonic rocks (mainly granites), typical of sedimentary and crystalline systems in Japan, various geological environment investigations have been carried out as part of studies for geological disposal safety assessments [7]. Based on these, both Neogene sediments and plutonic rocks are considered to have generally favourable characteristics from the viewpoint of waste confinement. The latest geoscientific findings obtained in JAEA's URLs projects [74] [92] [115] [116] are considered to support this [8].

Table 3.3-1 Characteristics of the five rock types from the viewpoint of geological disposal

Age	Neogene	Pre-Neogene	Pre-Quaternary	Pre-Quaternary	
Rock type	Sedimentary	Sedimentary	Volcanic	Plutonic	Metamorphic
Surface Abundance*1 (%)	15	41	18	18	8
500 m depth abundance*1 (%)	15	40	15	20	10
1,000 m depth abundance*1 (%)	10	45	10	25	10
Structure of water conducting features	Pore, Fracture	Fracture, Bedding cleavage	Fracture	Fracture, Dyke	Fracture, Schistosity
Logarithmic mean of bulk hydraulic conductivity*2 (m/s)	2.9×10^{-7}	4.7×10^{-7}	2.1×10^{-7}	5.5×10^{-8}	4.3×10^{-8}
Average and median of effective porosity*3 (%)	25-27	3.5-6.8	5.4-7.9	0.8-1.5	1.2-6.8
Average and median of thermal conductivity*3 (W/m K)	1.6-1.8	1.4-1.5	2.4-2.5	2.8-2.9	3.3
Average and median of uniaxial compressive strength*3 (MPa)	9-28	74-90	92-106	108-110	55-66

*1For geological environment excluding the area within 15 km from the centre of Quaternary volcanoes.

*2Logarithmic mean as representative value

*3Average and median as representative values, giving an indication of the distribution of data

Pre-Neogene sedimentary rocks are important basement rocks and are widely distributed in Japan [175], estimated to occupy almost half of the area at around 1,000 m depth, as shown in Table 3.3-1. These occur as aggregates of blocks of different sizes, separated by faults. Structures are extremely variable, e.g. not primarily stratified, including allochthonous or autochthonous rock blocks composed of various lithological facies, or stratified but lacking continuity. This rock is generally highly consolidated and hard, thus with water-conducting features and mechanical strengths similar to plutonic rocks and quite different to Neogene sedimentary rocks. Therefore, Pre-Neogene sedimentary rocks are also considered in this report as a representative host rock.

In addition to the features analysed for design and safety assessment of the repository, consideration of a wider spectrum of characteristics (e.g. mean values and ranges given in Supporting Report 3-13), shows that Neogene and Pre-Neogene volcanic rocks have characteristics similar to plutonic rocks from the viewpoint of repository design, and similar to Pre-Neogene sedimentary rocks from the viewpoint of safety assessment. From the 1:200,000 Japan geological map [65], about 90% of the metamorphic rocks distributed at the surface are low grade crystalline schist (e.g. phyllite) and high grade gneiss (e.g. amphibolite). There is a clear difference between the characteristics of crystalline schist and gneiss, the former with characteristics similar to Pre-Neogene sedimentary rocks and the latter similar to plutonic rocks (see Supporting Report 3-13 for details). For Neogene/Pre-Neogene volcanic and metamorphic rocks, therefore, design and safety of a repository can be assessed by applying the concepts and methods applied to Pre-Neogene sedimentary rocks and plutonic rocks.

Thus, in this report, plutonic rocks, Neogene sedimentary rocks (hereinafter Neogene sediments), and Pre-Neogene sedimentary rocks (hereinafter Pre-Neogene sediments) are considered as representative host rocks. By developing concepts and methods for the design and safety assessment of the repository for these three rock types, the key characteristics of the five representative host rocks (including Neogene/Pre-Neogene volcanic and metamorphic rocks) can be covered.

3.3.3 Development of a representative SDM

(1) Basic concept

The repository scale area is about several km × several km and should have favourable geological environment characteristics and long-term stability. It includes the repository host rock together with surrounding formations and associated structures. The larger regional scale area (several tens of km × several tens of km around the repository footprint) captures features that may impact perturbation phenomena and includes regional groundwater flow system from recharge to discharge, as well as hydraulic boundaries such as groundwater divides. A smaller panel scale area is around several hundred m × several hundred m within the repository scale area, encompassing a single waste disposal panel. In this area, the characteristics that affect the design of the engineered barriers and assessment of any radionuclide migration from them are evaluated in detail.

For the regional scale SDM, it is necessary to consider the topography and sea-land distribution, in addition to the geological environment extending from deep underground (≈ 2 km) to the surface. As discussed in Section 3.2.1, it is also necessary to conceptualise impacts of evolution of topography and geological structures caused by regional uplift and erosion, sea-level change, etc. Based on established exclusion criteria [2] to assure safety of both surface and underground facilities, these representative SDMs are developed that do not include any characteristics that would lead to their rejection during siting.

(2) Development of conceptual SDMs

(i) Plutonic rocks

More than 90% of plutonic rocks distributed at the surface are granites and these have been extensively studied at depth in JAEA's URLs at Mizunami and Kamaishi [92] [115] [116] [176], and a number of international URLs (e.g. Stripa and Äspö in Sweden and Grimsel in Switzerland). Therefore, granites are chosen as representative plutonic rocks.

The regional scale area was selected to be 50 km × 50 km (× 3 km depth), considering that granite bodies of this scale are widely distributed [174] and that the basin area of a large-scale river (considered to be the largest area within a groundwater hydraulic boundary) averages about 2,200 km^2. For the repository scale area, an area of 5 km × 5 km (× 1.5 km depth) was selected within the regional scale area, considering the scale and distribution of faults, the groundwater flow flux and the travel time from the repository to the area boundary. For this, the heterogeneity of the geological and hydrogeological characteristics of the rock mass surrounding the repository was modelled in more detail. For the panel scale area, based on an approach similar to that for the repository scale area, an area of 800 m × 800 m (x 100 m thickness) was specified in even greater detail in order to support design and safety assessment of the repository.

The conceptual SDM for plutonic rocks, covers an area that includes regional groundwater flow system from recharge to discharge areas and defines hydraulic boundaries, as shown in Figure 3.3-2. It includes basement granite, an upper highly fracture domain, (or weathered zone) with relatively high hydraulic conductivity (up to about 200 m in thickness), and a younger sedimentary overburden (about 100 to 200 m thick).

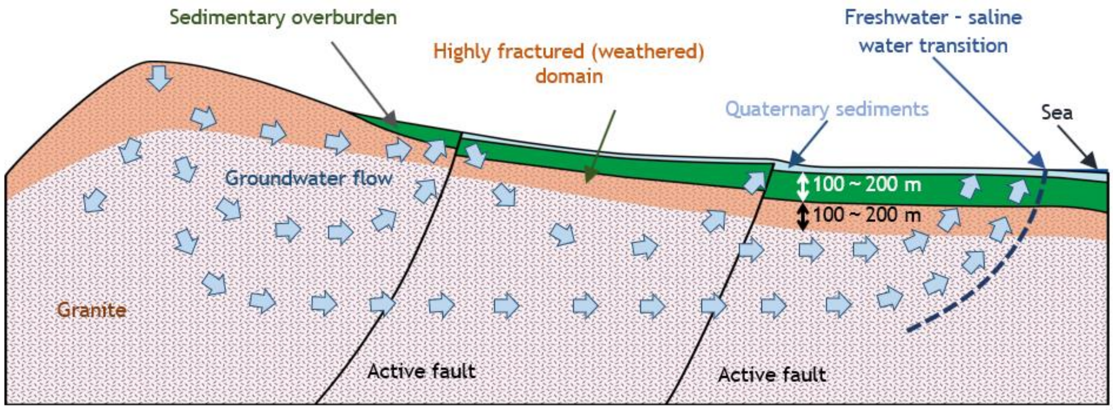

Figure 3.3-2 Conceptual SDM for plutonic rocks

Large scale faults in the granitic basement (discussed further in (3) (i) (a) below), generally include fault gouge with relatively low hydraulic conductivity surrounded by fault breccia and damage zones with a relatively high fracture density and high hydraulic conductivity. Anisotropy is often observed in their structural and hydraulic characteristics [47] [83] [92] [176] [177] [178] [179]. These features are found in all rocks in Japan, although their detailed characteristics will vary for different geological settings [177][180] [181] [182].

Deep groundwater has a downward flow in recharge areas, with upward flow associated with structural discontinuities and in freshwater-saltwater mixing areas/discharge areas near the coastline. For a regional groundwater flow system, groundwater flow at depth in central regions is predominantly horizontal, without being greatly affected by the surface topography [183]. Such horizontal groundwater flow may be affected by the spatial distribution of faults with anisotropic hydraulic conductivity.

The dataset used for plutonic rock is presented in Supporting Report 3-14, with information for establishing modelling areas and constructing associated SDMs presented in Supporting Report 3-15.

(ii) Neogene sediments

The regional scale area was selected to be 30 km × 30 km (× 2 km depth) taking into account distribution at the ground surface in the 1:200,000 Japan Geological Map [65], as well as the maximum thickness obtained from the 1:50,000 geological map and existing literature for 57 sedimentary basins where Neogene sediments are widely distributed. The repository scale area was selected to be 5 km × 5 km (× 1 km depth) considering the layout of the repository and spatial distribution of geological structures and groundwater flux/travel times. The panel scale area within the repository scale area was selected to be 800 m × 800 m (× 100 m thickness) similar to the plutonic rock case.

When constructing a SDM for Neogene sediments, again an area that includes groundwater flow system from recharge to discharge as well as hydraulic boundaries is represented, as shown in Figure 3.3-3. In this SDM, Neogene sediments overlie basement granite and older sediments and are covered by Quaternary sediments, which include a range of horizontal, vertical and fold structural elements.

In the Neogene sediments, large scale faults are represented and considered to be similar to those for plutonic rocks [74], as are the constraints on deep groundwater flow [183].

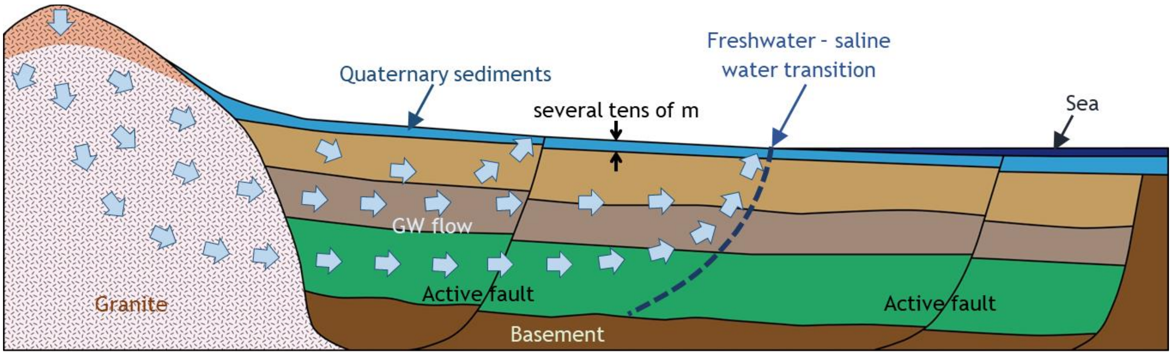

Figure 3.3-3 Conceptual SDMs for different Neogene sediment layers (shown in terracotta, light brown, and green). The basement (dark brown) is here assumed to consist of Paleogene sedimentary rocks

Supporting Report 3-16 presents the dataset used to construct the SDMs for Neogene sediments, and Supporting Report 3-17 presents basic information on the setting of modelling areas and construction of a conceptual SDM.

(iii) Pre-Neogene sediments

As most Pre-Neogene sediments exposed at the surface [67] correspond to accretionary complexes, these were the focus for SDM development. Considering the general features of accretionary complexes, including the development of thrusts and rupture/mixing of strata [184] [185], both simple coherent facies and more complex mélange facies were modelled.

A focus was placed on the literature information on the Ashio, Mino, Tamba, Chichibu, and Shimanto Belts [186] [187] [188] [189] [190], estimated to represent about 80% of the area of all accretionary bodies at the ground surface according to the 1:200,000 Japan Geological Map [65]. The regional scale area was selected to be 40 km × 40 km (× 3 km depth) taking into account the average area and thickness of these accretionary complexes, which can be considered as representative for Japan. The repository scale and panel scale areas were set at 5 km × 5 km (× 1.5 km depth) and 800 m × 800 km (× 100 m thickness), respectively, similar to plutonic and Neogene sediments as described above.

As for the other rocks, the SDM for Pre-Neogene sediments represents regional groundwater flow system from recharge to discharge areas as well as hydraulic boundaries, as shown in Figure 3.3-4. In addition, Pre-Neogene sediments consisting of units with different lithologies and stratigraphic boundaries, together with associated thrusts, faults and folds are represented.

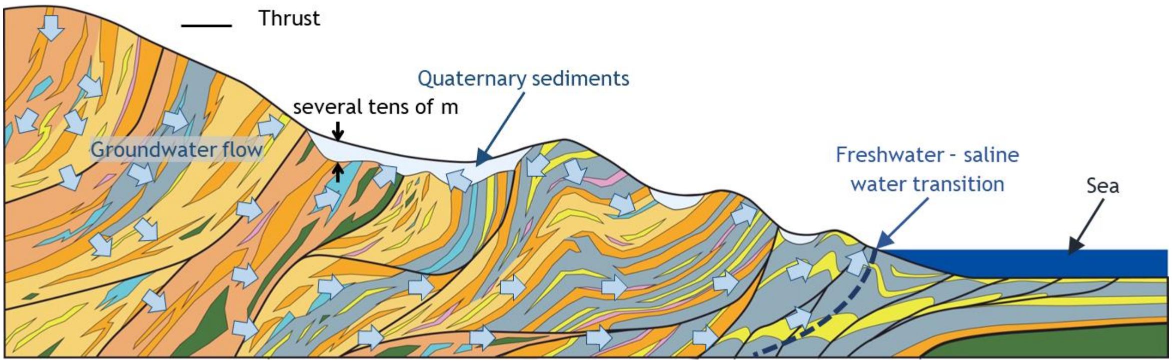

Figure 3.3-4 Conceptual SDM for Pre-Neogene sediments consisting of units with different lithologies and stratigraphic boundaries, together with associated thrusts (indicated by different colours)

Many thrusts of different scales develop within accretionary complexes [191]. In the Pre-Neogene sediments, in addition to thrusts, a range of other large faults will be present, the structural and hydraulic features of which are considered to be similar to those in plutonic rocks [181] [192]. Deep groundwater flow is considered, as for the other cases, to be largely horizontal except for recharge and discharge areas [183].

Supporting Report 3-18 presents the dataset used to construct the SDMs for Pre-Neogene sediments and Supporting Report 3-19 presents basic information on selecting modelling areas and construction of the conceptual SDM.

(3) Concept for development of geological and hydrogeological models

(i) Geological models

(a) Plutonic rocks

For plutonic rocks, faults and fractures are considered to play a greater role in defining groundwater flow and radionuclide migration than the rock matrix. Therefore, similar to cases where SDMs were developed from outcrop, geophysical and borehole investigations in overseas siting investigations [96] [97] [98] [99] [100] [101], the distribution of faults and fractures are modelled deterministically or stochastically within a discrete fracture network (DFN) model. Indeed, modelling of the Olkiluoto and Forsmark sites using DFN models has been accepted by the relevant regulatory organisations as a basis for safety assessment within applications for repository construction licenses [193] [194].

When carrying out geological modelling using DFN models, from the viewpoint of the ease of characterisation during the staged siting process, faults and fractures are classified by length as (A) 10 km or more, (B) 1-10 km and (C) less than 1 km. For (A), active faults may result in $M \geq 6.5$ earthquakes, which could potentially have a significant impact on underground facilities [195]. In this report, such faults would be excluded from the repository area during the literature survey stage or, at the latest, during the first half of the detailed investigation stage. Regarding (B), based on the results from the Mizunami URL programme [92][116], it was confirmed that it would be possible to roughly identify the position, structure and hydraulic characteristics of these at the LS stage or again, at the latest, during the first half of the DI stage. The frequency of occurrence of (B) is higher and potential impacts of fault movement less than (A), hence these may be permitted within the repository area, but excluded from the panel scale area. Because (C) would be numerous in the host rock, these are impossible to characterise completely during PI and DI stages and hence the purpose of the investigations is to understand their repository-relevant properties and to utilise statistical approaches to determine their integrated impact, e.g., assuming a fractal spatial distribution of faults and fractures [196].

Thus, the regional scale DFN model was developed by stochastically modelling the spatial distribution of all faults longer than 1 km, based on nationwide data. At the repository scale, based on groundwater flow analysis on the regional scale, a region with relatively long groundwater travel times was selected from the areas where faults longer than 10 km are not present. For faults with length of 1-10 km in the repository scale area, fault locations, strikes and dips (modelled stochastically at the regional scale area) were represented deterministically. In the panel scale model, because faults and fractures less than 1 km in length are distributed throughout, deterministic modelling was adopted as far as possible based on observations from tunnel walls. The stochastic approach was, however, used where the spatial distribution of the faults and fractures were not available. Details of the source information and its application is given in Section (4) below. It should be noted that the "length" of faults and fractures in this report corresponds to trace lengths measured at outcrops and tunnel walls.

For fault and/or fault zones with a scale of several km or more, a damage zone may develop asymmetrically around the fault plane [197] [198]. In other cases [47] [83] [92] [176] [177] [178], however, a core zone consisting of fault gouge and fault breccia with a thickness of a few metres, has a damage zone consisting of cataclasite and fractured rock that develops symmetrically on both sides (schematically shown in Figure 3.3-5).

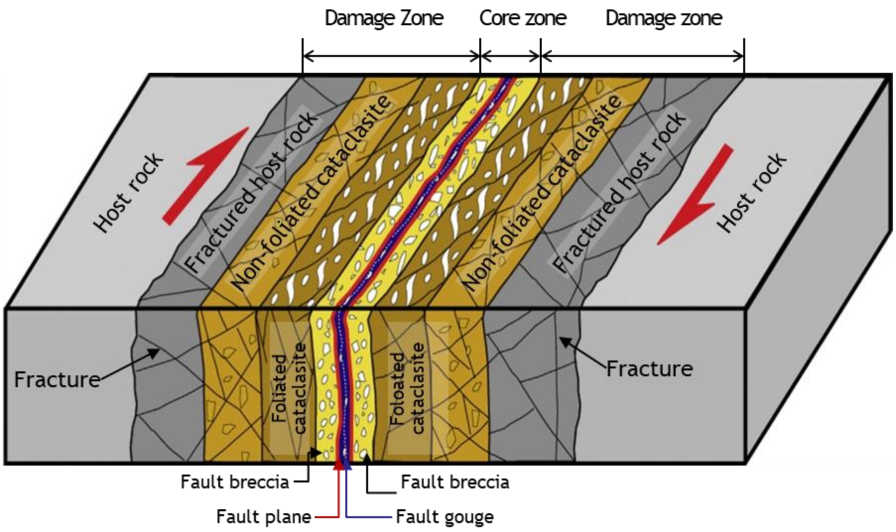

Figure 3.3-5 Conceptual geological model of a fault
(Edited from Lin and Yamashita, 2013 [198])

In particular, the density of fractures in the fault breccia and damage zone is higher than in the surrounding rock. Based on this, the conceptual geological model includes such features as the representative concept for faults with a scale of several km or more, assuming that the width of the fault impacted zone is about 1/100 of the fault length [46] [199]. These features are also found in Neogene and Pre-Neogene sediments.

In Supporting Report 3-14, a dataset of relevant nationwide geoscientific information is presented.

(b) Neogene sediments

The key geological features of Neogene sediments included in the geological model, as shown schematically in Figure 3.3-6, include the spatial distribution of faults and fractures together with their lengths and strikes/dips; lithology and thickness of sedimentary layers; inclination of monoclinic shear zones; wave lengths/wave heights/axial lengths/axial directions of folds; and lengths of horizontal/monoclinic/fold structures in a section perpendicular to the strike or dominant direction of strata.

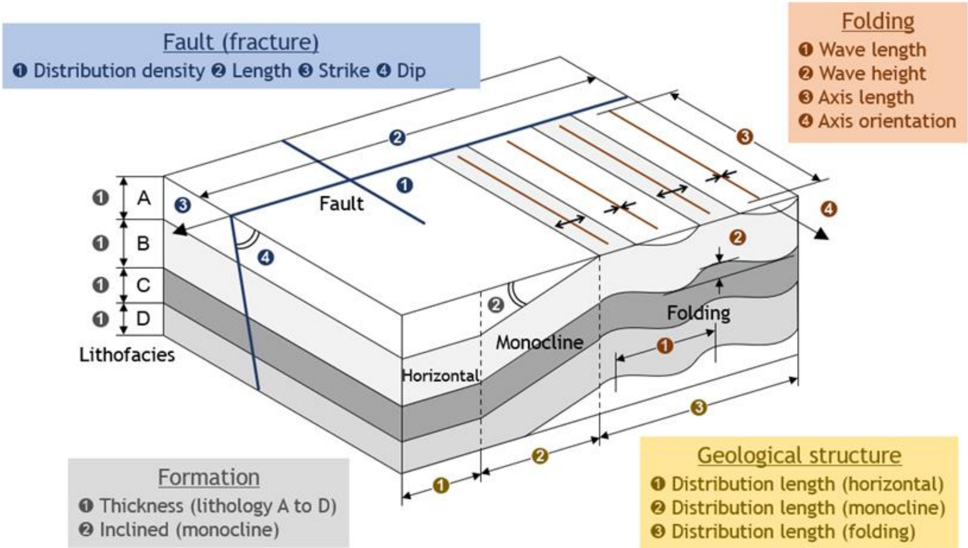

Figure 3.3-6 Parameters considered for the geological model of Neogene sediments

The parameter values (arithmetic mean) for each stratum, the fold structures and geological structures were derived from the information on Neogene sediments in the published 1:50,000 geological map. The abundance of Neogene sediments corresponds to about 70% of the entire distribution in the 1:200,000 Geological Map [65], and the selected parameter values were therefore considered to be representative of Japan. The process involved and the treatment of faults at repository and panel scales is discussed further in Section (4) below. In Supporting Report 3-16, the dataset of relevant nationwide geoscientific information is presented.

(c) Pre-Neogene sediments

Pre-Neogene sediments may comprise coherent facies, consisting of alternating sandstone and mudstone layers with good continuity, or mélange facies, containing a large number of rock blocks with mudstone as a matrix. Parameters for the geological model were determined based on the same approach as for Neogene sediments described above, using literature information on the Ashio, Mino, Tamba, Chichibu, and Shimanto Belts [186] [187] [188] [189] [190] [191] [200] [201] [202]. This allowed determination of accretionary complex thickness and slope, together with the wave length, wave height, axial length, axial direction, and plunge of large-scale fold structures (see Figure 3.3-7).

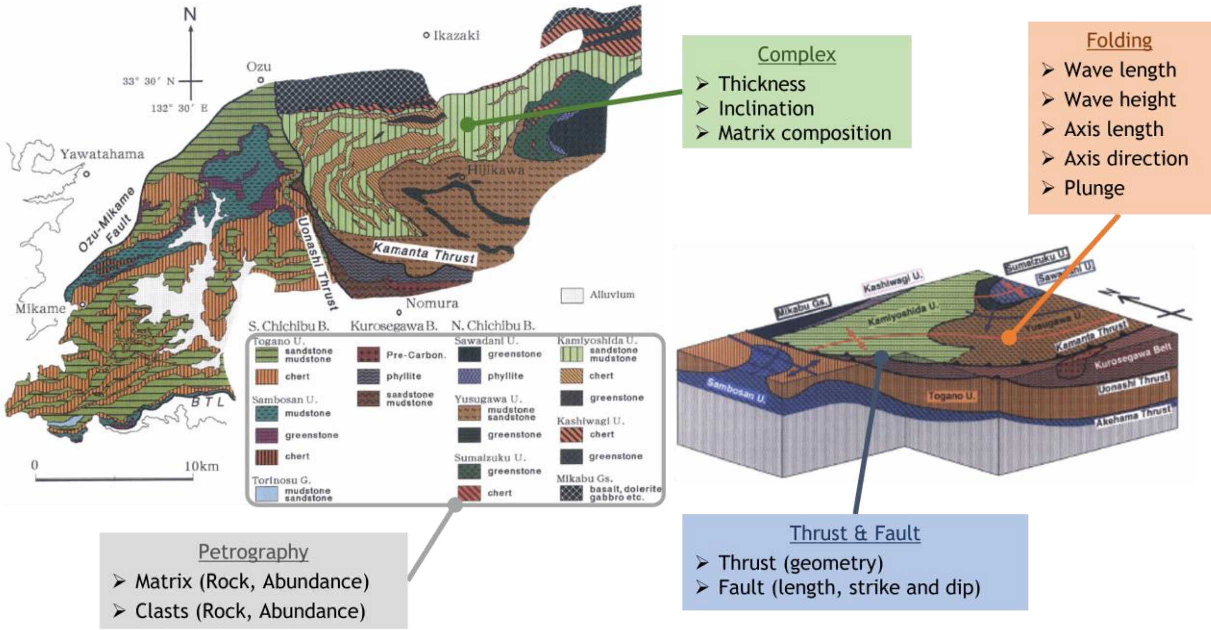

Figure 3.3-7 Parameters considered for the geological model of Pre-Neogene sediments (Modified from Matsuoka, 1998© Geological Society of Japan [186])

The ratio of the matrix and rock blocks that make up the accretionary complexes was determined using the 1:200,000 Geological Map of Japan [65]. Especially for the mélange facies, the geological model included stochastic descriptions of rock types and abundance/geometry of contained rock blocks. The process involved and the treatment of faults at repository and panel scales is discussed further in Section (4) below. In Supporting Report 3-18, the dataset of nationwide geoscientific information used is presented.

(ii) Hydrogeological models and groundwater flow analysis

(a) Hydrogeological models

For all representative host rocks, a continuum porous media (CPM) model that describes the spatial distribution of hydraulic characteristics was developed, capturing the heterogeneity of hydraulic conductivity due to differences in faults, fractures, and rock types that impacts groundwater flow on the regional and repository scale areas.

For large faults, fault gouge (shown in Figure 3.3-5) has relatively low hydraulic conductivity, however the surrounding damaged zones generally have high hydraulic conductivity [92] [178][179]. The entire fault was modelled taking into account such anisotropy, with hydraulic conductivity high parallel to the fault plane and low perpendicular to it. Depending on the rock type and fault formation processes, however, there are cases where there is little difference between the hydraulic conductivity of fault gouge and/or damage zones and that of the bulk rock [177].

The panel scale hydrogeology for plutonic rocks and Pre-Neogene sediments utilised DFN models including faults and fractures < 1 km in length, whereas that for Neogene sediments utilised a continuum model similar to that for the regional and repository scales. Table 3.3-2 summarises the hydrogeological models for the three rocks at different spatial scales.

Table 3.3-2 Outline for geological and hydrogeological models for each spatial scale

Scale/method		Plutonic rocks	Neogene sediments	Pre-Neogene sediments
Regional scale	Spatial scale	50 km × 50 km	30 km × 30 km	40 km × 40 km
	Modelling method	・ Geological model - Fault (> 1 km) distribution: Stochastic DFN[*1] ・ Hydrogeological model - Continuum	・ Geological model - Fault (> 1 km) distribution: Stochastic and deterministic DFN[*2] - Lithological distribution: Continuum ・ Hydrogeological model - Continuum	・ Geological model - Fault (> 10 km) distribution: Deterministic DFN - Fault (1-10 km) distribution: Stochastic and deterministic DFN[*3] - Lithological distribution: Continuum ・ Hydrogeological model - Continuum
Repository scale	Spatial scale	5 km × 5 km	5 km × 5 km	5 km × 5 km
	Modelling method	・ Geological model - Fault (1 - 10 km) distribution: Deterministic DFN[*4] - Fault/fracture (< 1 km) distribution: Stochastic DFN ・ Hydrogeological model - Continuum	・ Geological model - Fault (1 - 10 km) distribution: Deterministic DFN[*4] - Lithological distribution: Continuum ・ Hydrogeological model - Continuum	・ Geological model - Fault (1 - 10 km) distribution: Stochastic and deterministic DFN[*3] - Lithological distribution: Continuum ・ Hydrogeological model - Continuum
Panel scale	Spatial scale	800 m × 800 m	800 m × 800 m	800 m × 800 m
	Modelling method	・ Geological model - Fault/fracture (< 1 km) distribution: Stochastic DFN ・ Hydrogeological model - Stochastic DFN	・ Geological model - Fault/fracture (< 1 km) distribution: Stochastic DFN ・ Hydrogeological model - Continuum	・ Geological model - Fault/fracture (< 1 km) distribution: Stochastic DFN ・ Hydrogeological model - Stochastic DFN

[*1]DFN: Discrete fracture network.
[*2]The locations of faults (>1 km) are treated deterministically, taking into account their geological evolution
[*3]Only the dominant orientation of the fault (1 - 10 km) is treated deterministically.
[*4]The locations, strikes and dips of faults (> 1 km) are included in the regional scale geological model.

(b) Determination of hydraulic characteristics

In addition to nationwide dataset, for plutonic rocks and Neogene sediments, geoscientific information obtained from JAEA's URL programme [74] [92] [115] [116] was also used – in particular the transmissivity of faults/fractures based on borehole investigations. For Pre-Neogene sediments, the transmissivity of faults and fractures was determined based on literature information only.

(c) Groundwater flow analysis

Three-dimensional groundwater flow analysis was carried out on a regional scale for each rock, as indicated schematically in Figures 3.3-2 to 3.3-4, with a hydraulic gradient deep underground considered to be predominantly horizontal [183]. Based on the average hydraulic gradients in the lowlands, plateaus and hilly areas presented in the H12 report (0.01, 0.02, 0.04 respectively) [7] and the results of groundwater flow analyses conducted nationwide [203], the hydraulic heads at the boundaries were fixed to give a conservative hydraulic gradient of 0.05. The direction of the hydraulic gradient was set for two orthogonal directions (X and Y directions) in the model plane, considering the relationship between the groundwater flow direction and predominant directions of faults and fractures.

For repository scale three-dimensional groundwater flow analysis (see Sections (4) (ii) (b) and (c)), one of the two directions of the groundwater flow on the regional scale was selected. To assign appropriate boundary conditions in more detail than on the regional scale, the numerical model domains were selected to be larger than the repository scale area, dimensions of 10 km × 10 km (×1.5 km depth) for plutonic and Pre-Neogene sediments, and 7.5 km × 7.5 km (× 1 km depth) for Neogene sediments were selected for the analysis.

(4) Geological and hydrogeological models

(i) Regional scale

(a) Plutonic rock

Regardless of their scale, faults and fractures in granite tend to fall into two dominant vertical sets and a low-angle set, roughly orthogonal to each other [204]. Therefore, three fault sets were established (1-3) based on literature information [92] [176]. The length distribution of faults was determined by analysing the relationship between the trace length and areal density (number of faults per 1 m^2) based on:

- Active faults (Behavioural segments[6]) [41].
- Fault map of Japan [195].
- Calculation results of fault and fracture lengths based on wall observations in underground cavities [205].
- Observations of an outcrop in the Tono area (cumulative frequency distribution of fractures with a length of 10 m or less observed at the outcrop) [206].
- Lineaments longer than 100 m estimated from aerial photographs [7].

By overlaying the geological map at a depth of 500 m [174], i.e. the potential depth of the underground facilities, onto the information on the fault positions described in the fault map of Japan [195], the fault length distribution and areal intensity at a depth of 500 m were calculated.

As a result, it was confirmed that the relationship between the length and the cumulative areal density (fault length in metres per unit area m^2) of fault/fracture can be expressed by a power law (with an exponent of 4.0). The cumulative volumetric fault/fracture density was calculated from this using the theoretical conversion method of Wang (2005) [207]. The volumetric fault/fracture density longer than 1 km was determined as ≈ 0.001 m^2/m^3 and

[6] A behavioural segment is a fault section that divides an active fault into segments based on the timing of past activity, average displacement rate, average activity interval and the direction of displacement. N.B. This footnote is not included in the Japanese version of the report.

Figure 3.3-8 shows the relationship between the cumulative volumetric fault/fracture density and length.

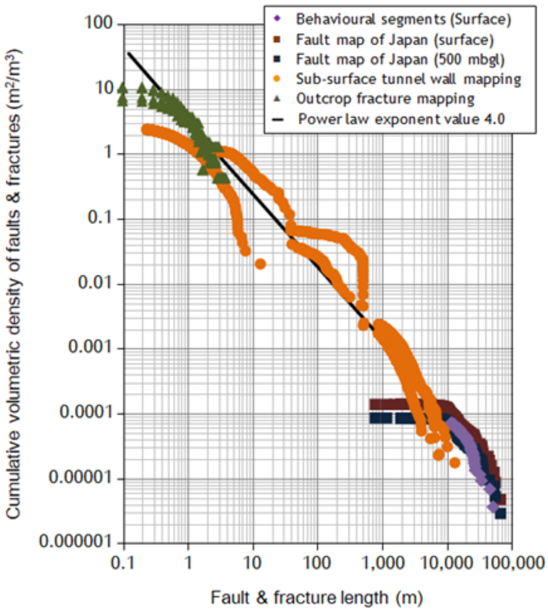

Figure 3.3-8 Relationship between fault length and volumetric density of faults and fractures in plutonic rocks

The key parameters used to develop the regional scale model are provided in Table 3.3-3. Figure 3.3-9 shows an example of a stochastically generated fracture model.

Table 3.3-3 Parameters used for the regional scale model of plutonic rock

Fault/fracture set	Orientation			Length	Volumetric density (m^2/m^3)
	Dip direction (°)	Dip angle (°)	Fisher coefficient[7]	Power law exponent value Minimum length (m) Maximum length (m)	
1 (NE-trending)	171	85	7.8	4.0 1,000 70,000	0.001
2 (NW-trending)	080	87	7.5		
3 (low angle)	203	01	8.4		

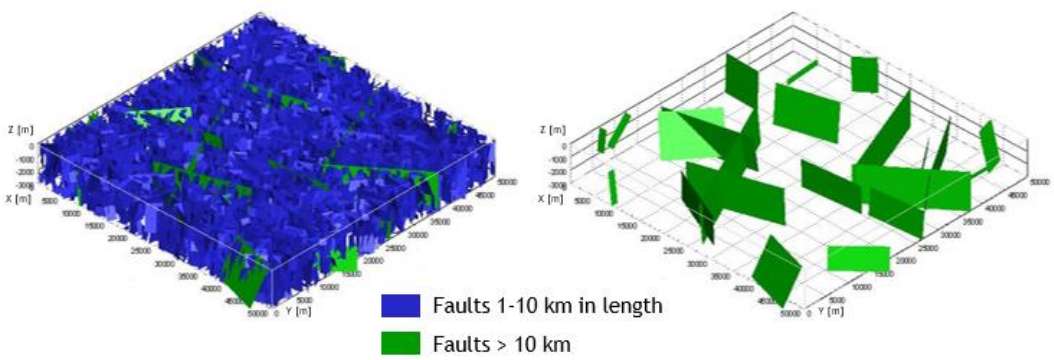

Figure 3.3-9 Regional scale geological model of plutonic rocks

[7] The Fisher coefficient indicates the variation in the orientation distribution. N.B. This footnote is not included in the Japanese version of the report.

The regional scale hydrogeological model was developed using hydraulic parameters of faults > ≈1 km length and a background fractured rock that incorporates properties of faults and fractures < 1 km long. For faults > 1 km, low hydraulic conductivity perpendicular to the fault plane and high hydraulic conductivity parallel to it were assigned based on the conceptual representation illustrated in Figure 3.3-5 (i.e., the hydraulic conductivity of fault gouge is low and that of fault breccia and damage zones is high [92] [178] [179]).

The hydraulic parameters used are presented in Table 3.3-4, while the resulting model is shown in Figure 3.3-10.

Table 3.3-4 Hydraulic parameters used for the regional scale hydrogeological model of plutonic rock

Hydrogeological unit	Direction & Hydraulic conductivity (m/s)	Remarks
Fault	Parallel to fault plane: 1.6×10^{-6} Perpendicular to fault plane: 1.3×10^{-9}	Only faults > ≈1 km
Rock matrix	1.4×10^{-8}	Also includes contribution from faults and fractures < 1 km

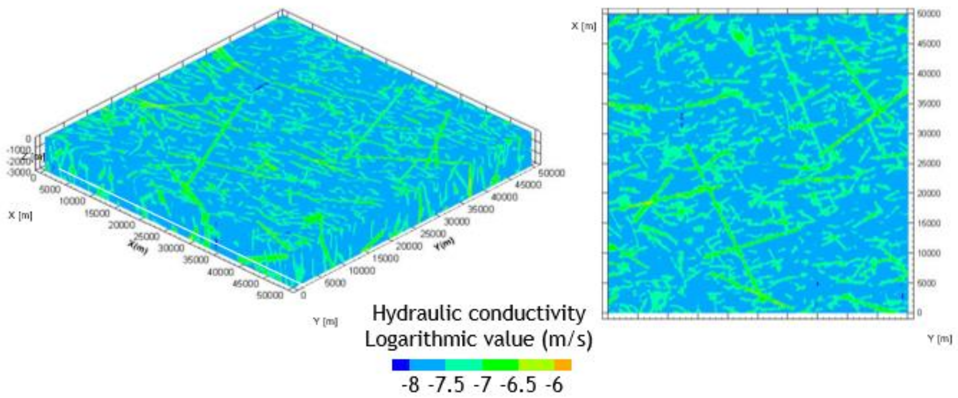

Figure 3.3-10 Regional scale hydrogeological model of plutonic rocks
Left: Perspective view, Right: Horizontal cross-section at repository depth of 1,000 m

Groundwater analysis at a regional scale was conducted for two groundwater flow directions in the horizontal plane to assess the relationship between the orientations of groundwater flow and predominant faults: Case 1 (flow in the X axis) and Case 2 (flow in the Y axis). From the Darcy flux distribution calculated, groundwater flow paths were identified and relative travel times were estimated by a particle tracking method, modelling movement of particles initially positioned at intervals of 100 m and at a depth of 1000 m (repository depth in plutonic rock; for details, see Section 4.3) within the domain of the facility (5 km × 5 km), groundwater flow paths and travel times were calculated to the downstream boundary.

It must be emphasised that the relative travel time (travel distance divided by Darcy flux) is a useful hydrologic characteristic, but should not be confused with the actual water travel time, which requires specification of the flow porosity of all water-conducting features. More importantly, this parameter cannot be related to solute transport times, even for non-sorbing species, as the latter requires specification of the characteristics of small-scale transport pathways (e.g. as shown in Figure 3.3-5).

Figure 3.3-11 shows examples of the head distribution calculated within the horizontal cross-section at a depth of 1000 m.

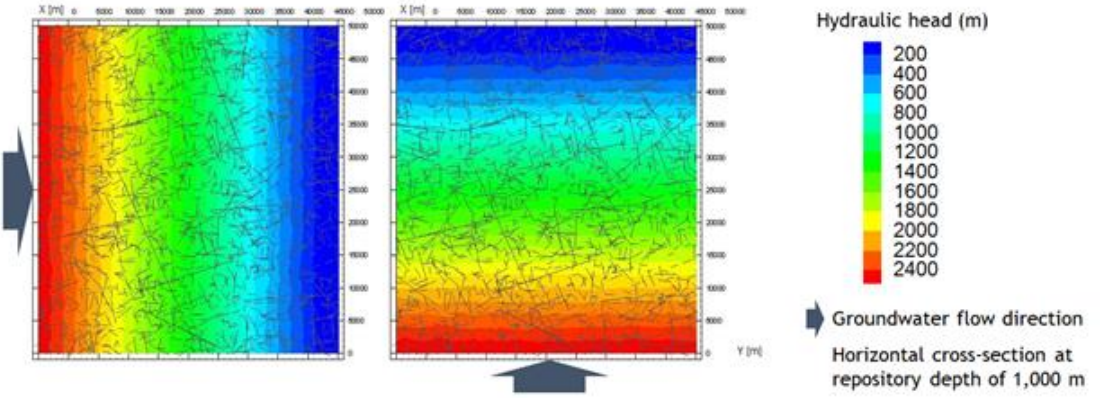

Figure 3.3-11 Head distribution at regional scale of plutonic rocks
Left: Case 1, Right: Case 2

Figures 3.3-12 and 3.3-13 show the Darcy flux distribution and the relative groundwater travel time to the downstream boundary, respectively.

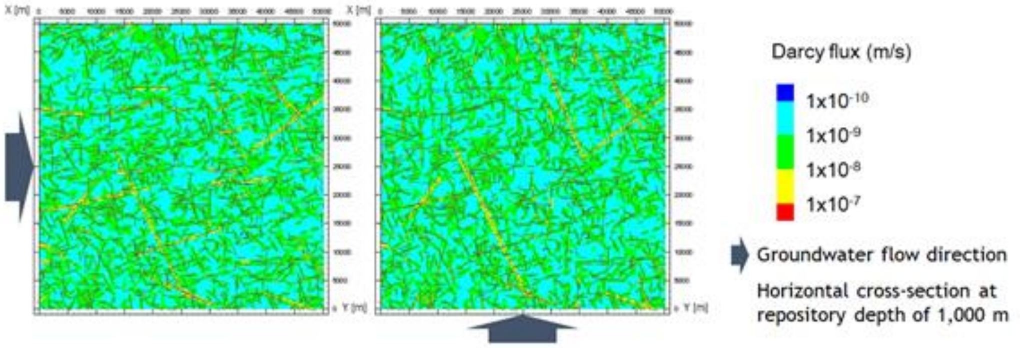

Figure 3.3-12 Darcy flux distribution at regional scale of plutonic rocks
Left: Case 1, Right: Case 2

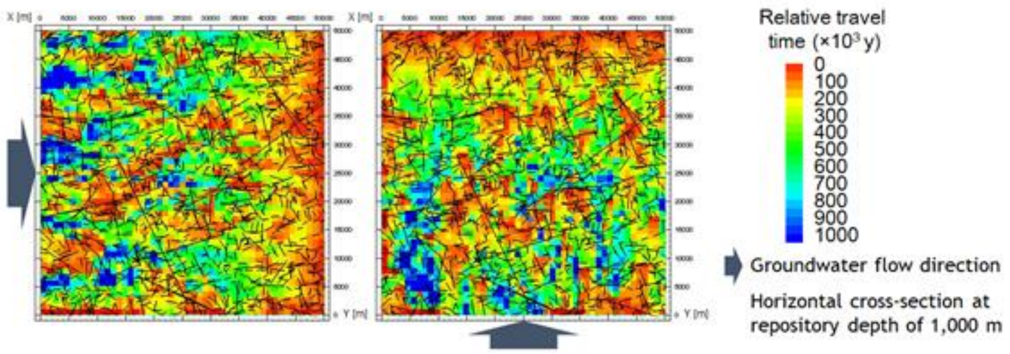

Figure 3.3-13 Relative groundwater travel time to the downstream boundary at regional scale of plutonic rocks; Left: Case 1, Right: Case 2

On the regional scale, although the iso-potential contour lines in Figure 3.3-11 are slightly perturbed by the difference in hydraulic conductivity between the background fractured rock and explicitly modelled faults, a groundwater flow field with an effectively constant hydraulic gradient is observed. The Darcy flux is larger in the faults, but almost constant otherwise. The relative groundwater travel time is short at positions where faults with a length of approximately 10 km or more are located or where multiple faults are connected in the direction orthogonal to the flow direction. In other areas, this travel time gradually decreases from upstream to downstream. This trend remains nearly the same, regardless of the direction of groundwater flow. The heterogeneity of hydraulic properties of plutonic rocks with a high density of faults and fractures thus has a small impact on groundwater flow, except in the vicinity of large or connected faults parallel to the groundwater flow direction.

Supporting Report 3-20 presents details of the development of the regional scale geological and hydrogeological models of plutonic rocks together with the associated groundwater flow analysis.

(b) Neogene sediments

Table 3.3-5 shows the parameters used for developing the regional scale geological model of Neogene sediments, based on the concept discussed in Section (3) (i) (b).

Table 3.3-5 Parameters used the regional scale geological model of Neogene sediments

<table>
<tr><th colspan="3">Parameter</th><th>Set value</th></tr>
<tr><td colspan="2">Length of geological structure</td><td>(km)</td><td>Horizontal 8 ± 1: Monoclinic 6 ± 1: Folding 16 ± 1</td></tr>
<tr><td colspan="2">Inclination of monoclinic structure</td><td>(°)</td><td>36±15</td></tr>
<tr><td rowspan="4">Folding</td><td>Wave length</td><td>(km)</td><td>3±1</td></tr>
<tr><td>Wave height</td><td>(km)</td><td>0.6±0.3</td></tr>
<tr><td>Axis length</td><td>(km)</td><td>3</td></tr>
<tr><td>Axis direction</td><td>(°)</td><td>8</td></tr>
<tr><td rowspan="4">Formation thickness</td><td>Mudstone</td><td>(m)</td><td>449, 449 (double layer)</td></tr>
<tr><td>Alternating mudstone & sandstone</td><td>(m)</td><td>311 (single layer)</td></tr>
<tr><td>Sandstone</td><td>(m)</td><td>462, 62 (double layer)</td></tr>
<tr><td>Conglomerate</td><td>(m)</td><td>268 (single layer)</td></tr>
</table>

For the predominant orientation of faults with a length of 1 km or more, four arbitrary directions were determined based on the behavioural segments [41] and the fault map of Japan [195]. As for the plutonic rock model, a power law (with an exponent of 3.3), which was assumed based on the relationship between the length and the cumulative areal density of faults/fractures, was applied to describe the length distribution .

The volumetric density was determined as 0.0003 m^2/m^3 from the relationship between the cumulative volumetric density and the length of the faults/fractures. Figure 3.3-14 shows the relationship between the cumulative volumetric fault/fracture density and length. It is noted that approximation straight line power law was applied though the fit line above the observed data to ensure that the volumetric density is derived conservatively (overestimated).

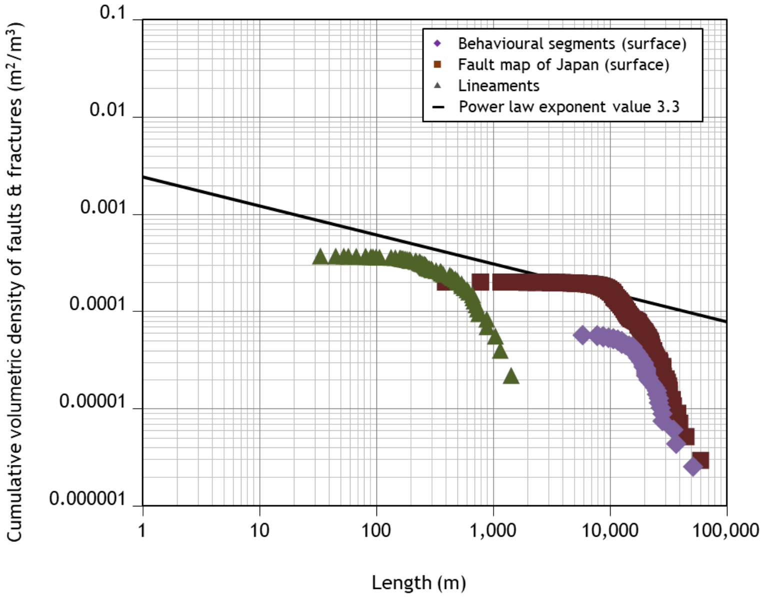

Figure 3.3-14 Relationship between the cumulative volumetric density and length of faults and fractures for Neogene sediments

Parameters used to model the spatial distribution of the faults on a regional scale are provided in Table 3.3-6.

Table 3.3-6 Parameters used for the regional scale geological model of Neogene sediments (spatial distribution of faults)

Fault/fracture set	Orientation			Length	Volumetric density (m^2/m^3)
	Dip direction (°)	Dip angle (°)	Fisher coefficient	Power law exponent value Minimum length (m) Maximum length (m)	
1	246	84	7.4	3.3 1,000 70,000	0.0003
2	324	90	24		
3	286	41	9.6		
4	103	44	15		

In the development of the regional scale model, the impacts of changes in the regional stress field since the Neogene [208] [209] were considered. As shown in Figure 3.3-15, this considers rifting by normal faults under tensile stress in the early Neogene, prior to sedimentation during the middle Neogene while the rift evolves, and then uplift/tilting/folding associated with the movement of reverse faults under compressive stress from the late Neogene to the Quaternary.

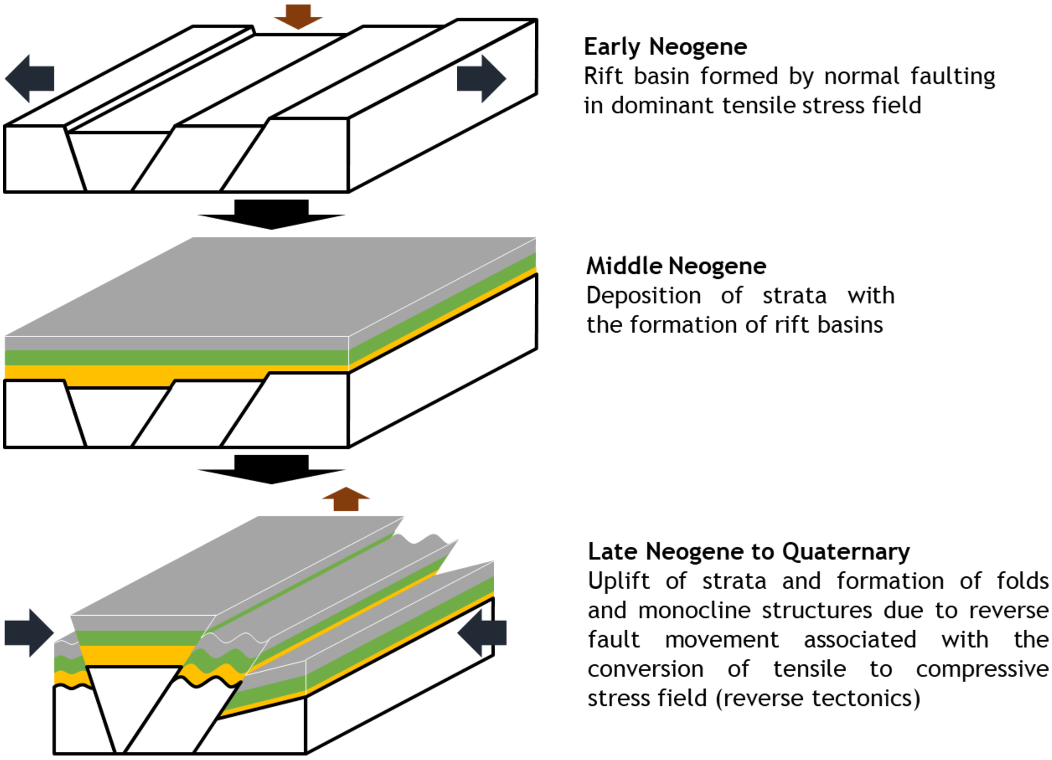

Figure 3.3-15 Developmental history of the geological structure of Neogene sediments

The geological structure and spatial distribution of lithofacies were modelled based on the parameters in Table 3.3-5, after uplift and tilt of the strata had been assessed deterministically. Figure 3.3-16 shows the resulting regional scale model.

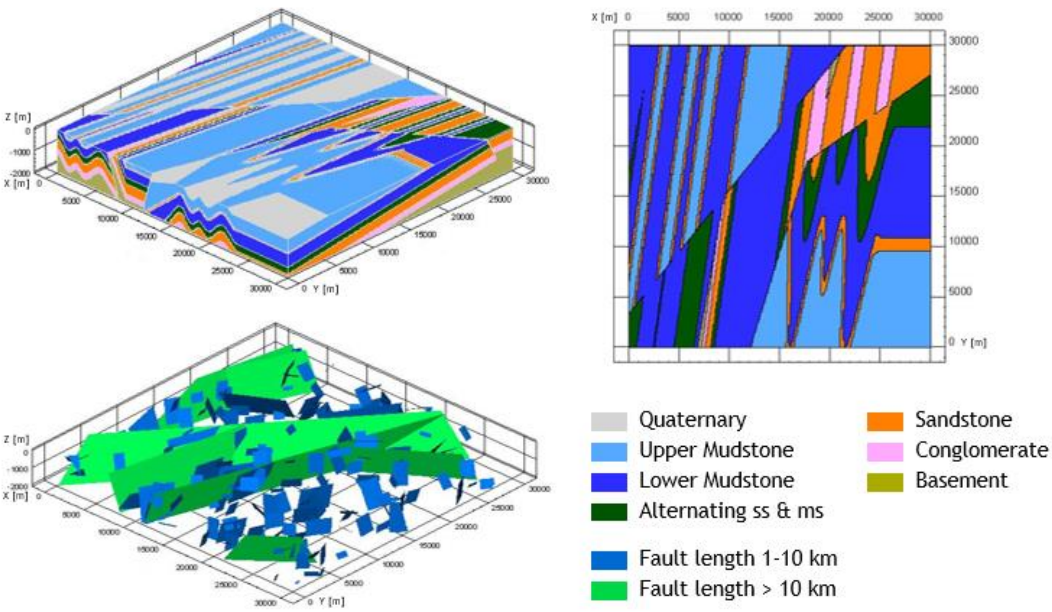

Figure 3.3-16 The regional scale geological model of Neogene sediments
Upper left: perspective view, Lower left: spatial distribution of faults, Right: Horizontal cross-section at repository depth of 500 m

The regional scale hydrogeological model was developed by determining the hydraulic parameters of each facies and also faults with a length > ≈ 1 km. In particular, for such faults, fault gouge and fault breccia/damage zones are considered (as shown in Figure 3.3-5). However, based on a case study indicating that the anisotropy of hydraulic conductivity is less than that in plutonic rocks [210], an isotropic hydraulic conductivity value was assigned for the entire fault (including both core zone and damage zone).

The parameters used to develop the regional scale model are given in Table 3.3-7 and the result presented in Figure 3.3-17.

Table 3.3-7 Parameters used for the regional scale hydrogeological model of Neogene sediments

Hydrogeological unit	Hydraulic conductivity (m/s)	Remarks
Quaternary	1.0×10^{-5}	
Mudstone	2.3×10^{-8}	
Alternating sandstone and mudstone	Vertical: 2.3×10^{-8} Horizontal: 5.3×10^{-7}	Vertical: identical to mudstone Horizontal: identical to sandstone
Sandstone	5.3×10^{-7}	
Conglomerate	6.5×10^{-8}	
Basement	1.1×10^{-8}	
Fault	5.4×10^{-7}	Length > 1 km

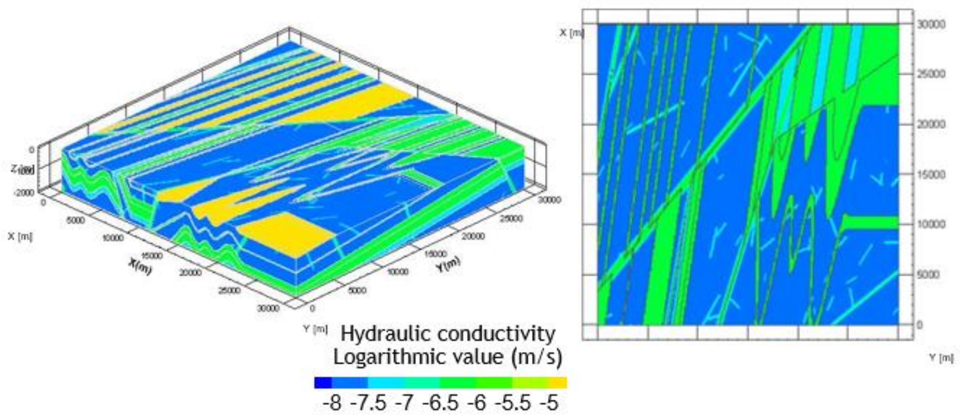

Figure 3.3-17 Regional scale hydrogeological model of Neogene sediments
Left: Perspective view, Right: Horizontal cross-section at cross-section depth of 500 m

The groundwater analysis using the regional scale hydrogeological model was conducted for two horizontal groundwater flow directions as for plutonic rocks; Case 1 (flow in the X axis) and Case 2 (flow in the Y axis). Using the Darcy flux distribution of the groundwater flow analysis results, the groundwater flow paths were identified using a particle tracking method.

Figure 3.3-18 shows the head distribution obtained by the groundwater flow analysis at the repository depth of 500 m.

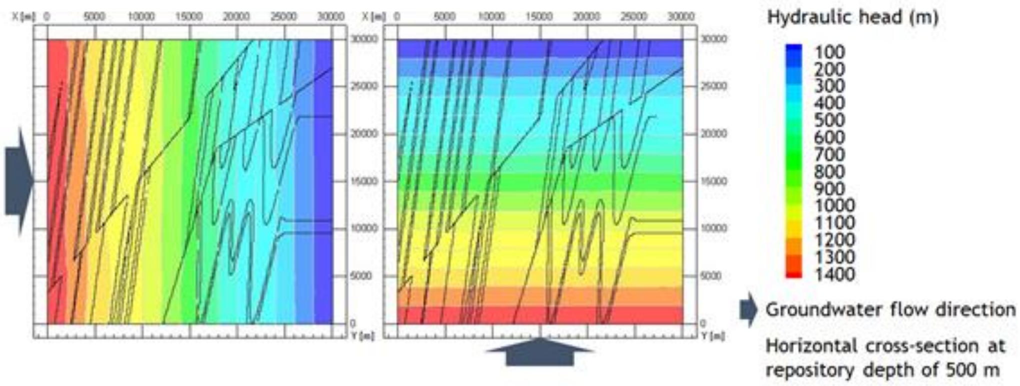

Figure 3.3-18 Head distribution at the regional scale for Neogene sediments Left: Case 1, Right: Case 2

Figures 3.3-19 and 20 show the Darcy flux distribution and the relative groundwater travel time to the downstream boundary, respectively

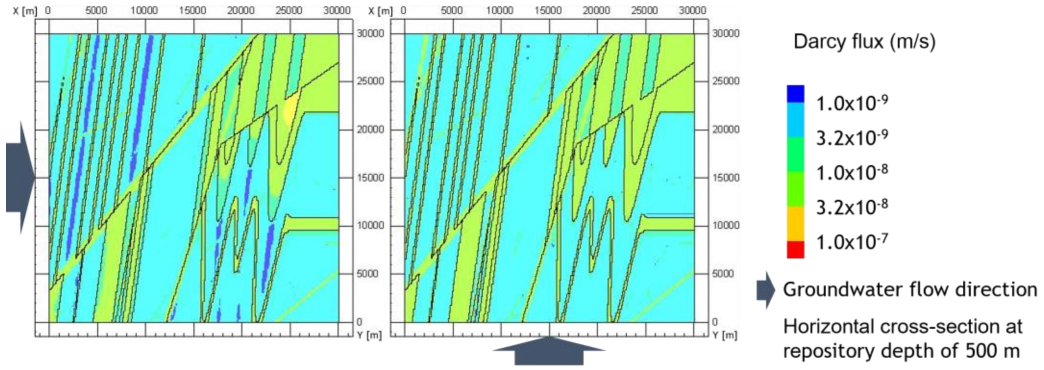

Figure 3.3-19 Darcy flux distribution at the regional scale for Neogene sediments. Left: Case 1, Right: Case 2

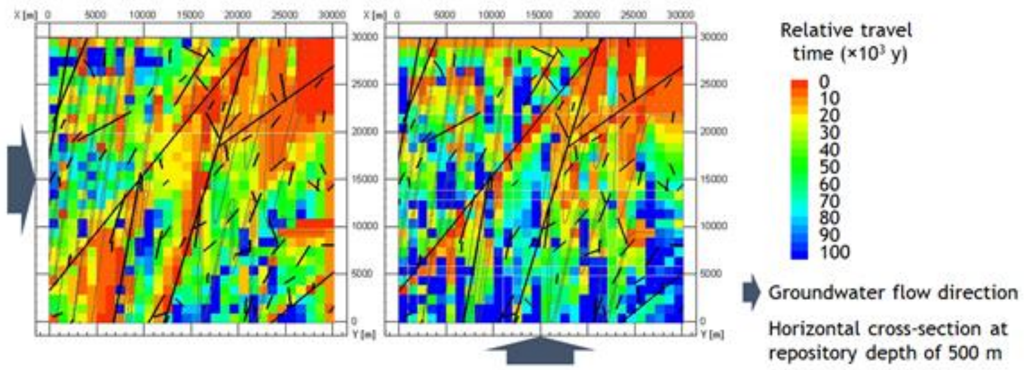

Figure 3.3-20 Relative groundwater travel time to the downstream boundary on the regional scale for Neogene sediments. Left: Case 1, Right: Case 2

On the regional scale, for Case 1, the groundwater flow direction intersects the predominant orientation of the faults (NNE-SSW to NE-SW) and formations (NNE-SSW) at a large angle (tending towards perpendicular). In contrast, for Case 2, the intersecting angle is small (tending towards parallel). This explains differences in the iso-potential contours and, in particular, the Darcy flux for the two cases.

Supporting Report 3-21 presents the details on the development of the regional scale geological and hydrogeological models of Neogene sediments together with the associated groundwater flow analysis.

(c) Pre-Neogene sediments

In developing the regional scale geological model of Pre-Neogene sediments, the parameters for accretionary complexes, fold structures and lithology (see Figure 3.3-7) were determined based on an analysis of the literature [186] [187] [188] [189] [190] [191] [200] [201] 202], described previously in Section (3) (i) (c).

The distribution of coherent and mélange facies within a single accretionary complex, as well as the rock fractions contained therein, were derived from the 1:200,000 Geological Map of Japan [65]. For the coherent facies, parameters were determined with reference to the Shimanto Belt, which is predominantly comprised of this facies. For the mélange facies, the parameters were determined with reference not only to the Ashio, Mino, Tamba and Chichibu Belts, where mélange facies are dominant, but also the Tokoro, Hidaka, Idonnap, and Northern Kitakami Belts, considering the heterogeneity of lithology described later.

For the lithology of the coherent facies, based on Nakae (2000) [188], mudstone-dominant matrix (ms), sandstone-dominant matrix (ss) and rock blocks (chert) were assumed. For the mélange facies, the type and abundance ratio of rock blocks and matrix were determined based on data from the accretionary complexes noted above.

The accretionary complex was modelled based on the parameters shown in Table 3.3-8.

Table 3.3-8 Parameters used for the regional scale geological model (geological structure and lithofacies) of Pre-Neogene sediments

Parameter			Selected value
Accretionary complex	Thickness	(m)	2,500
	Inclination	(°)	50
	Matrix composition	(%)	Coherent facies: 0-5, Mélange facies: 20-40
Folding	Wave length	(km)	20
	Wave height	(km)	6
	Axial length	(km)	10
	Axial orientation	(°)	90
	Plunge	(°)	0-25W
Lithology	Matrix/composition	(%)	Coherent facies: ms dominant 50, ss dominant 50 Mélange facies: Mudstone 100
	Matrix/composition	(%)	Coherent facies: Chert 100 Mélange facies: Greenstone 45, Chert 40, Ultramafic rock 10, Limestone 5

Different accretionary complexes come into contact at thrusts [186] [191], as shown in Figure 3.3-4. Thrusts of 10 km or more that separate the accretionary complexes are expressed deterministically as boundaries in the model. For faults 1 to 10 km long in coherent facies, the cumulative areal density of faults/fractures was approximated by a power law with a conservatively assumed exponent of 4.0 (Figure 3.3-21) based on data from behaviour segments [41], the fault map of Japan [195], and fault/fracture lengths observed on tunnel walls [205]. The model was then developed with the azimuth and inclination determined deterministically to match the entire geological structure (folding and thrust distribution).

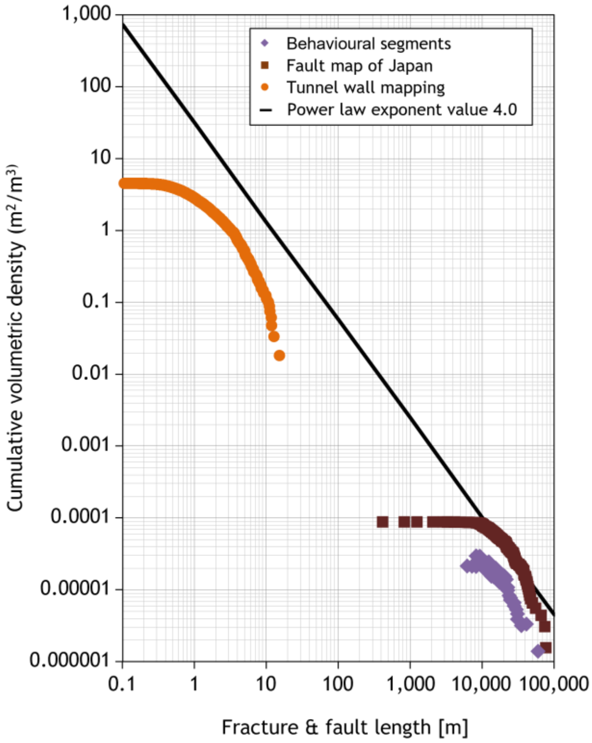

Figure 3.3-21 Relationship between cumulative volumetric density and length of faults and fractures for Pre-Neogene sediments

For mélange facies, the model was constructed with the azimuth and inclination set deterministically, but assuming that about 30% of faults 1 to 10 km long correspond to out-of-sequence thrusts, formed independently of the internal structure of the old accretionary complex, based on the 1:50,000 scale geological map of the Chichibu Belt distributed in the Kanto, Shikoku and Kyushu regions.

Figure 3.3-22 shows examples of regional scale geological models of coherent and mélange facies resulting from this process.

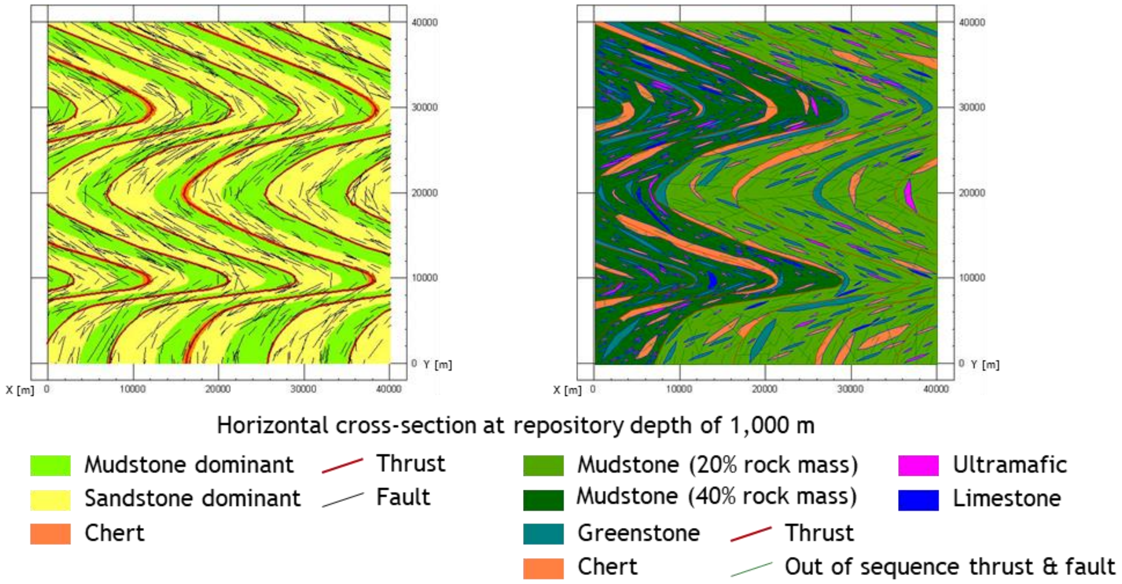

Figure 3.3-22 Regional scale geological models of Pre-Neogene sediments
Left: Coherent facies model, right: Mélange facies model

For the coherent facies, hydraulic parameters were determined for thrusts over 10 km in length, mudstone-dominant layers, sandstone-dominant layers, and rock blocks (chert). The geological information on Pre-Neogene sediments collected nationwide is, however, relatively limited compared to plutonic rocks and Neogene sediments, and is extremely limited below 300 m. When deeper data were available, these were used, otherwise it was assumed that the depth dependence of the data observed for other rock types would hold. For the mélange facies, because no data on the differences in the hydraulic parameters as a function of the rock block abundance were available, these were determined assuming that the mélange facies has macroscopically homogeneous properties on regional scale, except for large thrusts. The hydraulic conductivity of thrusts longer than 10 km was determined from the permeability measured for large faults within the Pre-Neogene sediments constituting the accretionary complex [181] [182] [192].

From this analysis, it was confirmed that hydraulic conductivity of deep Pre-Neogene sediments could be less than that of background fractured rock of plutonic rock (including faults and fractures of less than 1 km in length) or mudstone layers of Neogene sediments. The hydraulic parameters used for the regional scale hydrogeological model are summarised in Table 3.3-9 and the resulting models are shown in Figure 3.3-23.

Table 3.3-9 Hydraulic parameters used for the regional scale hydrogeological models for Pre-Neogene sediments

Hydrogeological unit		Hydraulic conductivity (m/s)	Remarks
Thrust		1.0×10^{-8}	Length > 10 km
Coherent facies	Matrix	2.0×10^{-9}	ms dominant, ss dominant
	Rock mass	1.0×10^{-8}	Chert
Mélange facies	Matrix	2.0×10^{-9}	
	Rock mass		

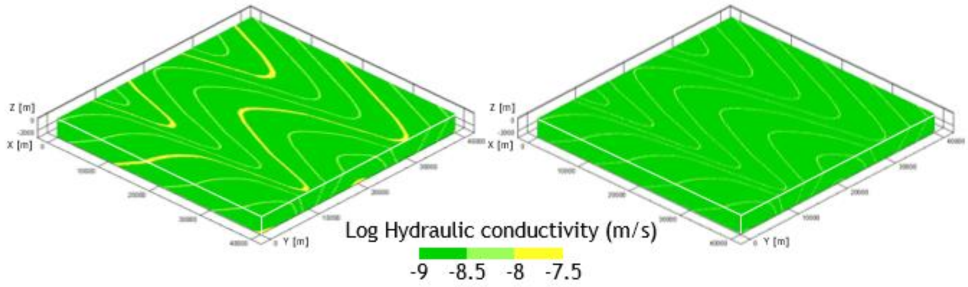

Figure 3.3-23 Regional scale hydrogeological models of Pre-Neogene sediments
Left: Coherent facies, right: Mélange facies

Again, the groundwater flow analysis was conducted for two groundwater flow directions. Using the Darcy flux distribution of the groundwater flow analysis results, the groundwater flow paths and travel times were estimated based on the particle tracking method.

Figure 3.3-24 shows the head distribution obtained by the groundwater flow analysis within the horizontal cross-section at the repository depth of 1000 m. Figures 3.3-25 and 3.3-26 show the Darcy flux distribution and the relative groundwater travel time to the downstream boundary, respectively.

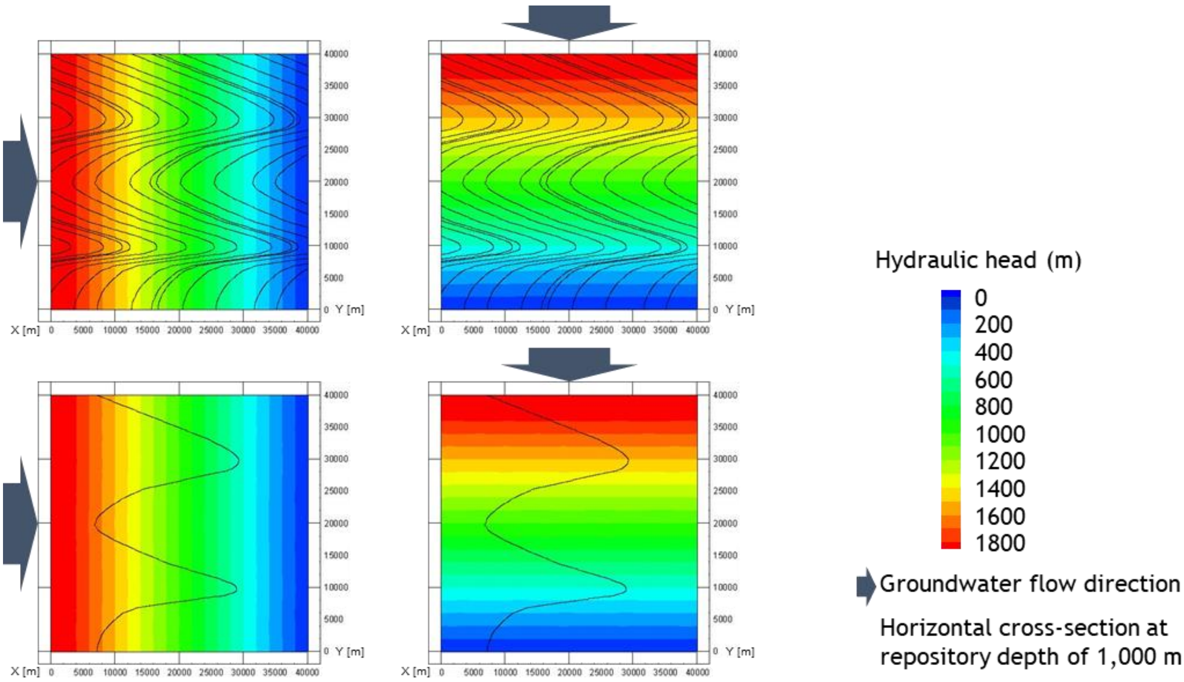

Figure 3.3-24 Head distribution at the regional scale for Pre-Neogene sediments
Upper left: Coherent facies (Case 1), Upper right: Coherent facies (Case 2)
Lower left: Mélange facies (Case 1), Lower right: Mélange facies (Case 2)

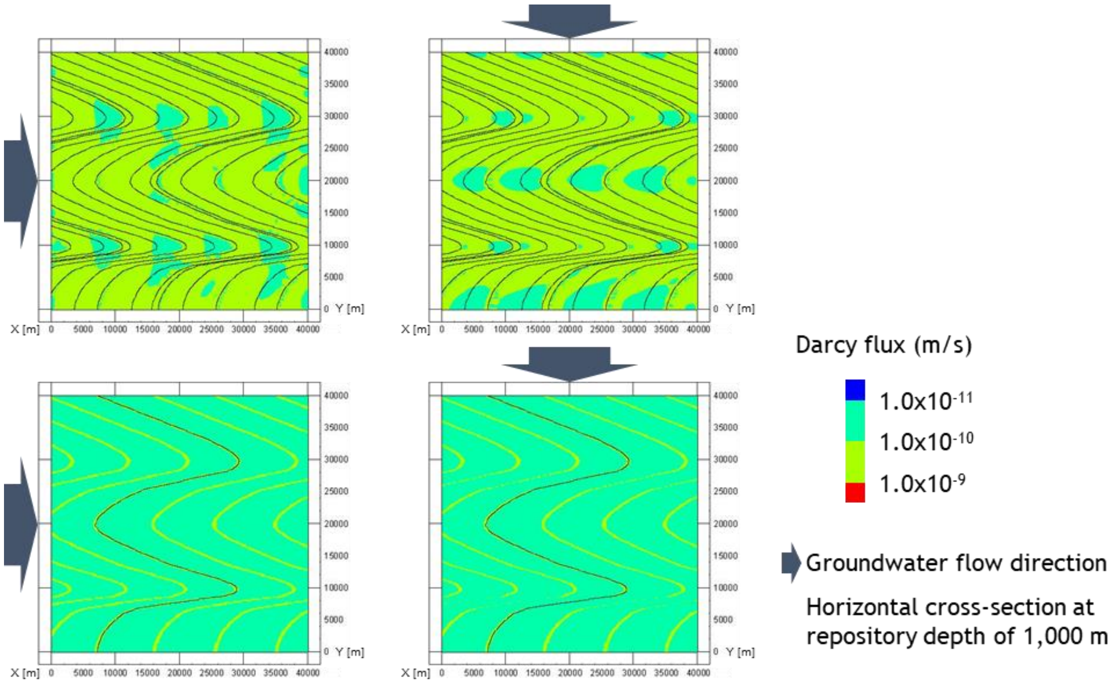

Figure 3.3-25 Darcy flux distribution at the regional scale for Pre-Neogene sediments
Upper left： Coherent facies (Case 1), Upper right： Coherent facies (Case 2)
Lower left： Mélange facies (Case 1), Lower right： Mélange facies (Case 2)

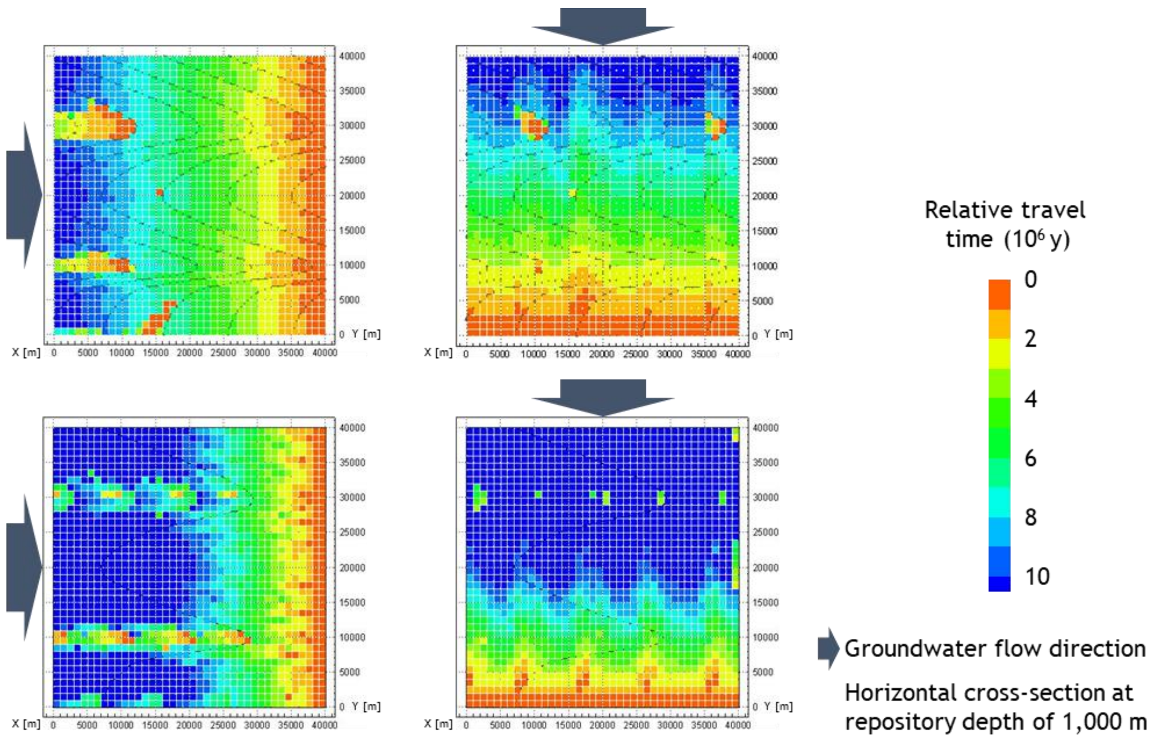

Figure 3.3-26 Relative groundwater travel time to the downstream boundary at a regional scale of Pre-Neogene sediments
Upper left: Coherent facies (Case 1), Upper right: Coherent facies (Case 2)
Lower left: Mélange facies (Case 1), Lower right: Mélange facies (Case 2)

On the regional scale, the hydraulic gradient from upstream to downstream was uniform due to the low contrast of hydraulic properties between thrusts, matrix and rock blocks.

Although the Darcy flow flux in the coherent facies was small compared to mélange facies, where the area between thrusts was narrow in the direction of groundwater flow, the travel time was generally short because flow occurred at a relatively high flux along the thrust.

In Case 2 (flow in Y axis direction) where the groundwater flow direction intersects the thrusts with a high angle, there was a tendency for less flow along thrusts compared to Case 1 (flow in X axis direction) where the intersection angle is low.

Supporting Report 3-22 presents details on the development of the regional scale geological and hydrogeological models of Pre-Neogene sediments together with the associated groundwater flow analyses.

(ii) Repository scale

(a) Plutonic rocks

The regional scale groundwater flow analysis showed that Darcy flow flux distributions were similar regardless of the direction of groundwater flow (Figures 3.3-12 and 3.3-13). The repository scale area was thus determined after arbitrarily selecting the groundwater flow as Case 2 (flow in Y direction). In particular, the regional scale area excludes faults with a length of 10 km or longer (represented by the green planes in the right figure of Figure 3.3-9 and the red lines in the left figure of Figure 3.3-27) as well as the areas potentially impacted by them. Thus, an area with a relatively low fault/fracture density and long groundwater travel time (see Figure 3.3-13) was selected (Figure 3.3-27).

Faults with a length of 1 km or more in the repository scale geological model were modelled deterministically using fault locations, strike and dip derived from the regional scale geological model (see Figure 3.3-9). Faults and fractures less than 1 km in length were modelled stochastically, assuming that the minimum fracture length that can be determined from boreholes is 1 m, using the same statistical distribution of faults and fractures (see Table 3.3-3) as the regional scale geological model. Figures 3.3-27 and 3.3-28 show the selected repository scale area and the derived geological model, respectively.

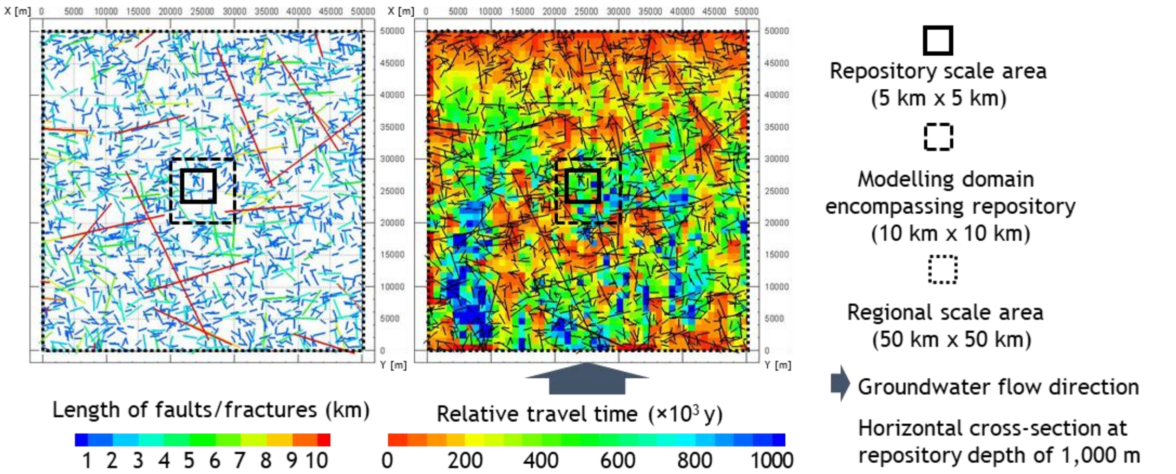

Figure 3.3-27 Selection of the repository scale area for plutonic rocks
Left: Geological model, right: groundwater travel time distribution (from Figure 3.3-13 right)

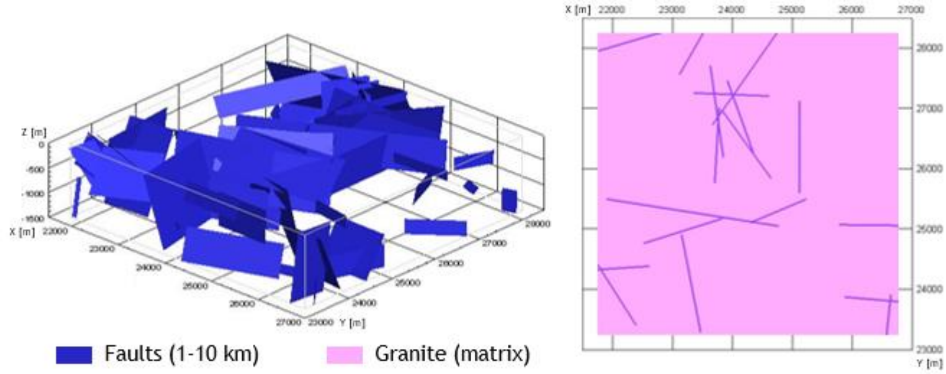

Figure 3.3-28 Repository scale geological model for plutonic rocks
Left: 3D visualisation, right: Horizontal cross-section at repository depth of 1,000 m

As for the regional scale, the repository scale hydrogeological model includes deterministically modelled faults longer than 1 km and background fractured rock (including faults and fractures shorter than 1 km) with appropriate hydraulic parameters, as given in Table 3.3-10.

Table 3.3-10 Hydraulic parameters used for the repository scale hydrogeological model of plutonic rocks

Hydrogeological unit	Hydraulic conductivity (m/s)	Remarks
Fault	Parallel to fault plane 1.6×10^{-6} Perpendicular to fault plane 1.3×10^{-9}	> 1 km in length
Rock matrix	2.7×10^{-8}	Including faults and fractures < 1 km in length

For the hydraulic conductivity of the background fractured rock, equivalent hydraulic conductivities for DFN model realisations were calculated and an average value used. The resultant hydrogeological model is illustrated in Figure 3.3-29.

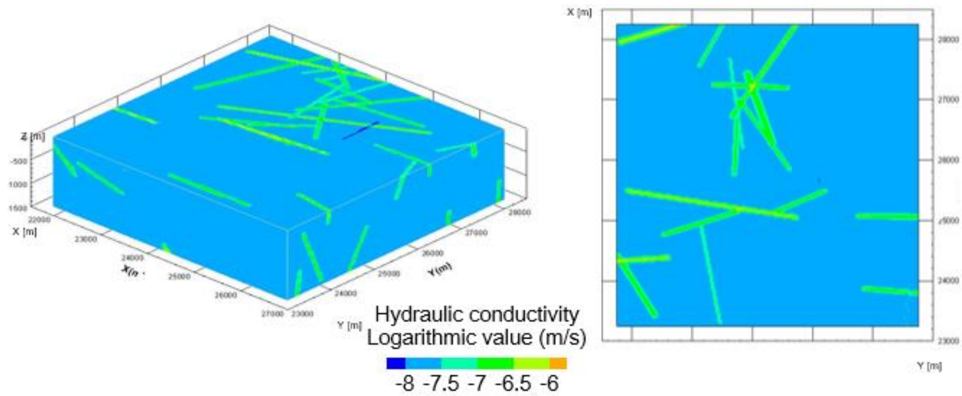

Figure 3.3-29 Repository scale hydrogeological model of plutonic rocks
Left: 3D visualisation, right: Horizontal cross-section at the repository depth of 1,000 m

Groundwater flow analysis at the repository scale was carried out by imposing fixed head conditions at the boundaries, based on the head distributions obtained from the regional scale analysis (Figure 3.3-11). Figures 3.3-30 and 3.3-31 show the resultant head and Darcy flux distributions, respectively.

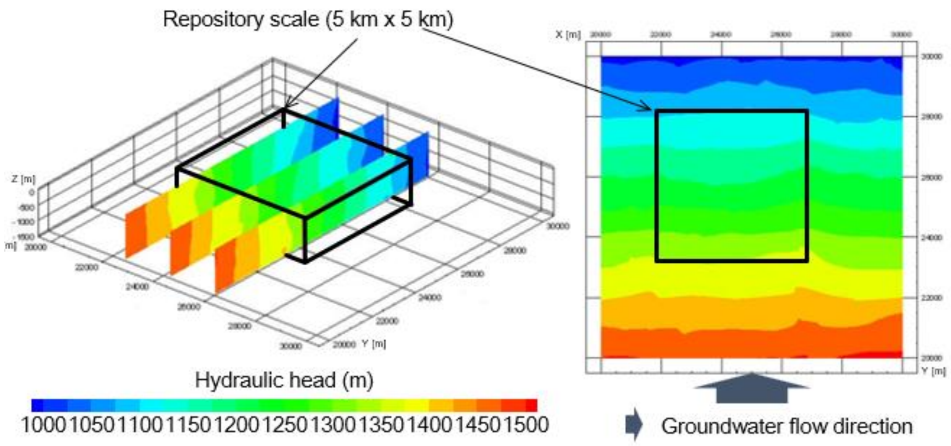

Figure 3.3-30 Head distribution at the repository scale for plutonic rocks
Left: Vertical cross-sections, right: Horizontal cross-section at a repository depth of 1,000 m

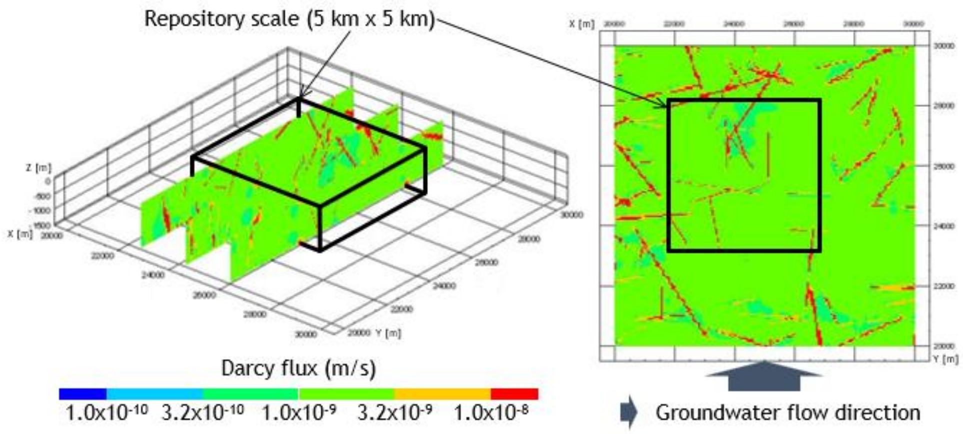

Figure 3.3-31 Darcy flux distribution at the repository scale for plutonic rocks
Left: Vertical cross-sections, right: Horizontal cross-section at a repository depth of 1,000 m

Figure 3.3-32 shows the distribution of relative groundwater travel times, which is used for determining the area where the repository will be located (for details, see Section 4.5.4 (1)). These times assume a distance of 500 m, set as the shortest distance from the repository to the model boundary. This clearly shows that groundwater travel times tend to be relatively short in and upstream of faults.

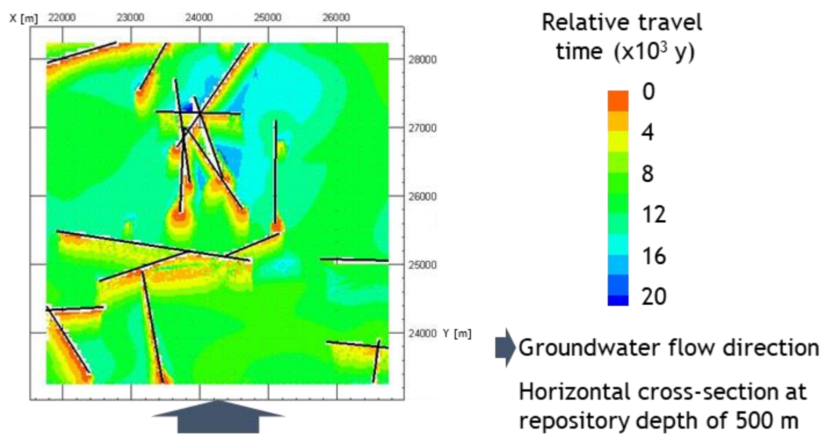

Figure 3.3-32 Groundwater travel time distribution (for 500 m) at the repository scale for plutonic rocks

The details of the repository scale geological and hydrogeological models as well as the groundwater flow analyses are provided in Supporting Report 3-23.

(b) Neogene sediments

The selection of the repository scale area took into account the need to make the areas sufficiently large to allow adjustment of the layout to meet the requirements for engineering feasibility and long-term post-closure safety, based on the regional scale geological model (see Figure 3.3-16) and groundwater flow analysis (see Figures 3.3-18 to 3.3-20). In particular, as a requirement to ensure the stability of disposal tunnels, it is preferred that the axial direction of such tunnels is aligned with the direction of maximum stress in the horizontal plane. From the viewpoint of reducing the influence of groundwater flow on the release of radionuclides, however, it may be preferred that the axial direction of the disposal tunnel is orthogonal to the groundwater flow direction (for details, see Section 4.5.4 (3)). The two groundwater flow directions considered, Case 1 (flow in the X direction) and Case 2 (flow in the Y direction), need to be assessed for compressive stress aligned in the X direction as defined in the regional scale model. For Case 1, the boundary conditions are more challenging as the two requirements conflict when tunnel orientation is being decided. In order to examine the issues involved, this is selected as the reference case for the SDM.

Areas with relatively long groundwater travel times were first selected, based on the regional scale groundwater flow analysis (see Figure 3.3-20). Then, taking account the complex geological structures that may be encountered in this rock, an area with a fold structure and multiple lithological units was arbitrarily selected to allow assessment of the layout of disposal areas and other underground facilities (for detail, see Sections 4.5.4 (1), (3) and (6)) and associated post-closure safety assessment (see Sections 6.4.1 (4) and (6)).

Figures 3.3-33 and 3.3-34 show the selected repository scale area and resultant geological model, respectively.

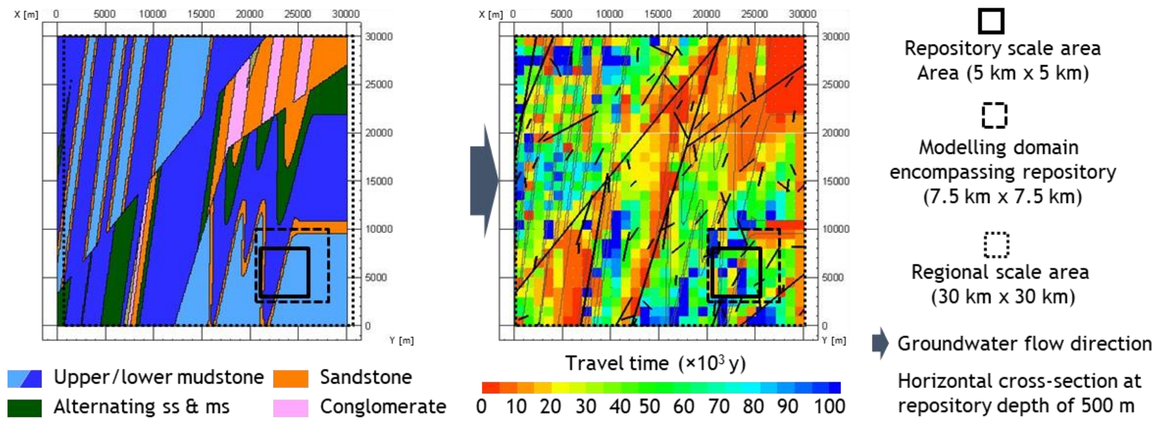

Figure 3.3-33 Selection of the repository scale area for Neogene sediments
Left: Geological model (from Figure 3.3-16 right), Right: Groundwater travel time distribution (from Figure 3.3-20 left)

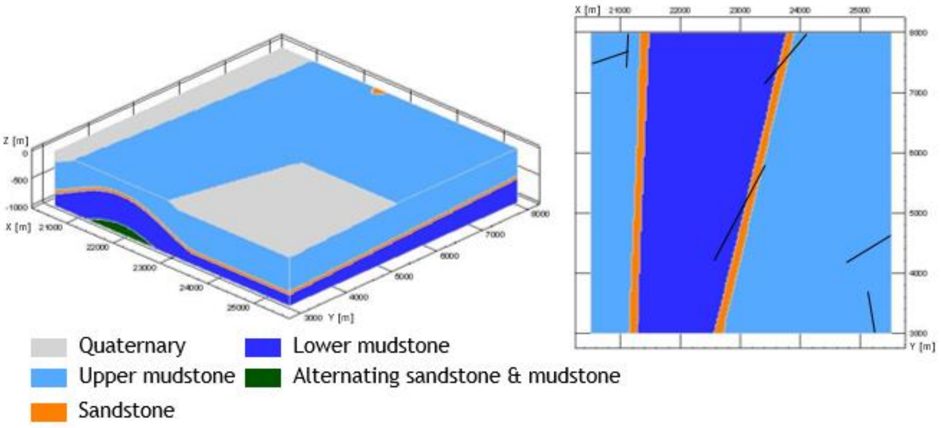

Figure 3.3-34 The repository scale geological model for Neogene sediments
Left: 3D visualisation, right: Horizontal cross-section at a repository depth of 500 m

In the repository scale hydrogeological model, different hydraulic conductivity values were assigned to the mudstone layers above and below the 62 m thick sandstone layer. The hydraulic parameters used for developing the repository scale hydrogeological model are provided in Table 3.3-11.

Table 3.3-11 Hydraulic parameters used for the repository scale hydrogeological model of Neogene sediments

Hydrogeological unit	Hydraulic conductivity (m/s)	Remarks
Quaternary	1.0×10^{-5}	
Upper mudstone	2.0×10^{-9}	Calculated from the panel scale DFN model Logarithmic mean of equivalent hydraulic conductivity distribution
Lower mudstone	4.4×10^{-8}	
Alternating sandstone and mudstone	Vertical: 2.3×10^{-8} Horizontal: 5.3×10^{-7}	Vertical: logarithmic mean of upper and lower mudstone layers Horizontal: same as sandstone layers
Sandstone	5.3×10^{-7}	
Fault	5.4×10^{-7}	> 1 km in length

The developed hydrogeological model is shown in Figure 3.3-35.

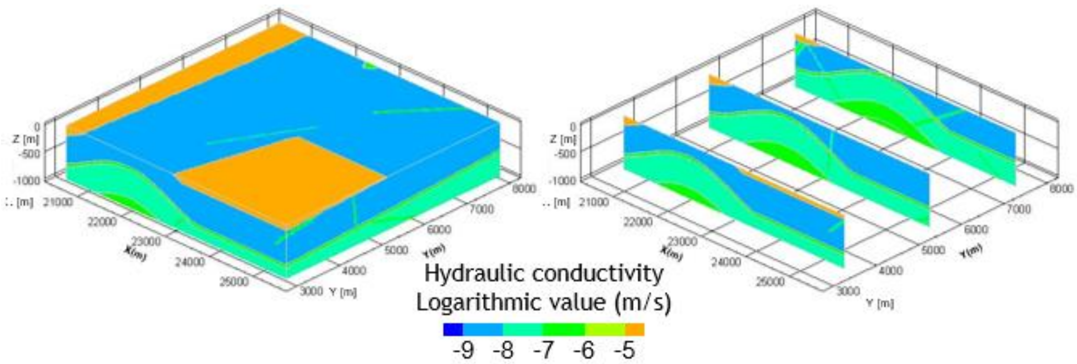

Figure 3.3-35 The repository-scale hydrogeological model of Neogene sediments
Left: 3D visualisation, right: Vertical cross-section

Groundwater flow analysis at the repository scale imposed fixed hydraulic heads at the boundaries based on results of the regional scale groundwater flow analysis (Figure 3.3-18).

As shown in Figure 3.3-36, the head distributions indicate downwards flow in the shallow part (upper mudstone layer) on the upstream side, while, on the downstream side, the flow was almost horizontal with only a slight downwards component.

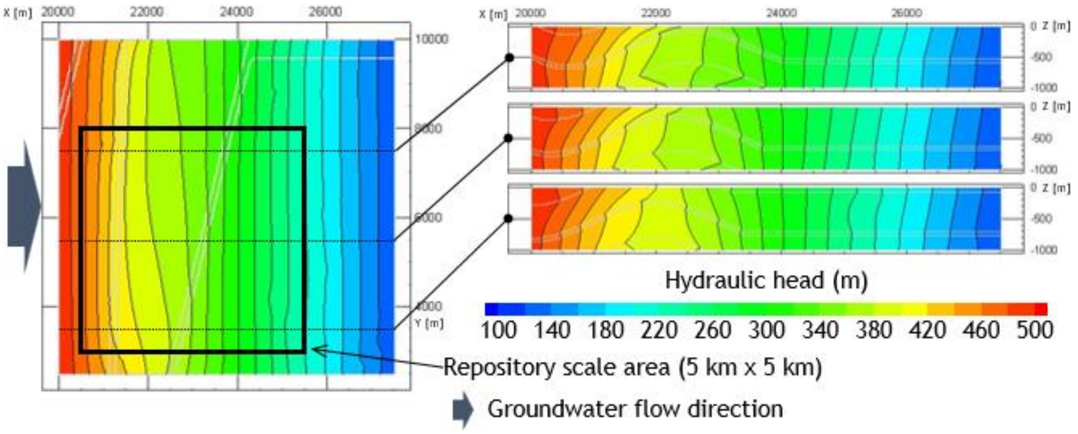

Figure 3.3-36 Head distribution at the repository scale for Neogene sediments Left: Horizontal cross-section at depth of 500 m, right: Vertical cross-sections

The Darcy flux distribution obtained is shown in Figure 3.3-37.

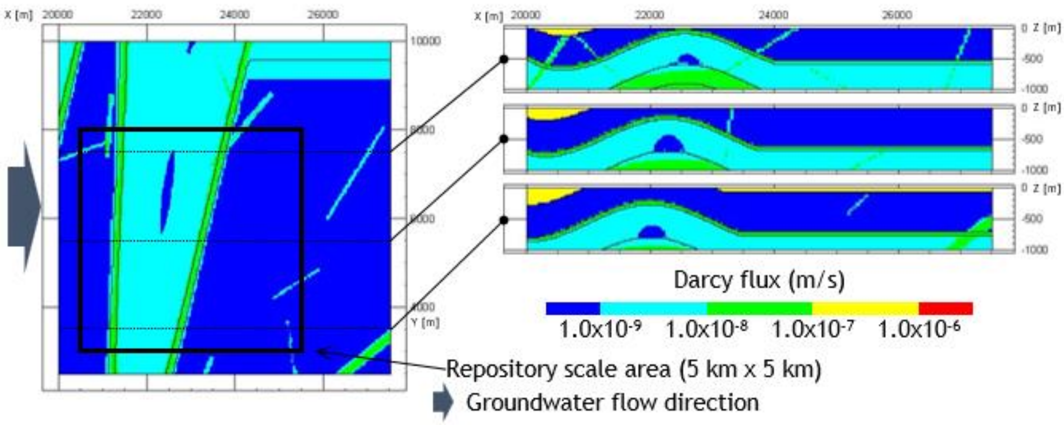

Figure 3.3-37 Darcy flux distribution at the repository scale for Neogene sediments. Left: Horizontal cross-section at a repository depth of 500 m, right: Vertical cross-sections

Figure 3.3-38 shows the distribution of relative groundwater travel time over a distance of 500 m (for details, see Section 4.5.4 (1)) calculated from the Darcy flux distribution in a horizontal section at a repository construction depth of 500 m, which is used to select the area where the repository will be located.

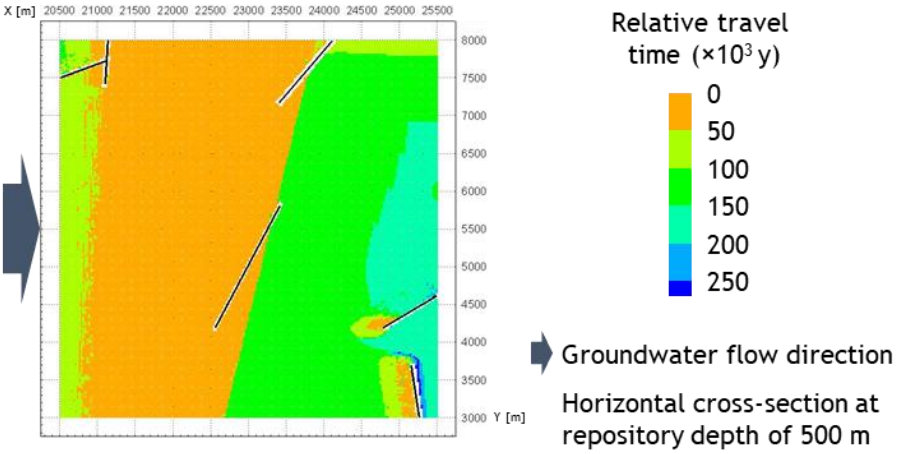

Figure 3.3-38 Relative groundwater travel time distribution at the repository scale for Neogene sediments.

The details of the repository scale geological and hydrogeological models as well as associated groundwater flow analyses are provided in Supporting Report 3-24.

(c) Pre-Neogene sediments

The repository scale area was selected based on the results of regional scale groundwater flow analysis (see Figures 3.3-24 to 3.3-26), excluding thrusts with a length of 10 km or more (see Figure 3.3-22).

For coherent facies, the Darcy flux and groundwater travel time distribution obtained from the groundwater flow analysis (see Figure 3.3-25 upper left and upper right figures and Figure 3.3-26 upper left and upper right figures), show a tendency for fast groundwater flow along the thrusts in Case 2 (flow in the Y direction) that is less apparent in Case 1 (flow in the X direction). Thus, groundwater flow direction in Case 2 was selected as the reference for further study in this report.

Areas with relatively small Darcy flux were first selected, based on the distribution at the repository depth of 1,000 m from the regional scale groundwater flow analysis (see Figure 3.3-25, upper right). Then, taking account of the complex geological structures that may be encountered in such rocks, an area where multiple facies are distributed was arbitrarily selected for further design studies, (for detail, see Sections 4.5.4 (1), (3) and (6)) and associated post-closure safety (for detail, see Sections 6.4.1 (4) and (6)). Figure 3.3-39 shows the repository scale area selected for the coherent facies.

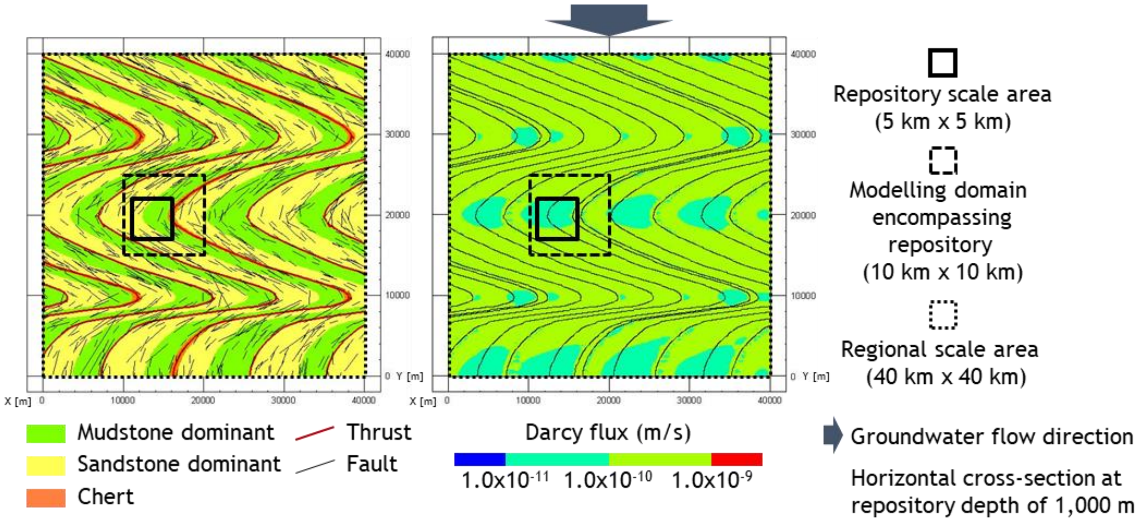

Figure 3.3-39 Selection of the repository-scale area for Pre-Neogene sediments. Coherent facies, left: Geological model (reshown, see Figure 3.3-22 left), right: Darcy flux distribution (reshown, see Figure 3.3-25 upper right)

For mélange facies, as discussed in Section (4) (i) (c), an arbitrary modelling domain was selected as the spatial variations in head, Darcy flux, and relative groundwater travel time from the regional scale groundwater flow analysis were small (Figures 3.3-24 to 3.3-26) due to the homogeneous hydraulic properties assumed for all components, except thrusts (Figure 3.3-23).

Faults with a length of 1 km or more (whose spatial distribution could be derived from site investigations) were modelled deterministically. Their strikes/dips were determined to be consistent with those of thrusts that are 10 km or longer. For mélange facies, it is difficult to support a deterministic model for the spatial distribution of rock blocks of various sizes and shapes [186] [188] [191] [200] [201] [211] [212], even following geophysical and borehole investigations. The spatial distribution of rock blocks was thus modelled stochastically, assuming that sufficient information on the types of rock blocks and their one- or two-dimensional distribution could be obtained by site investigations.

Figure 3.3-40 shows the repository scale geological models for coherent and mélange facies.

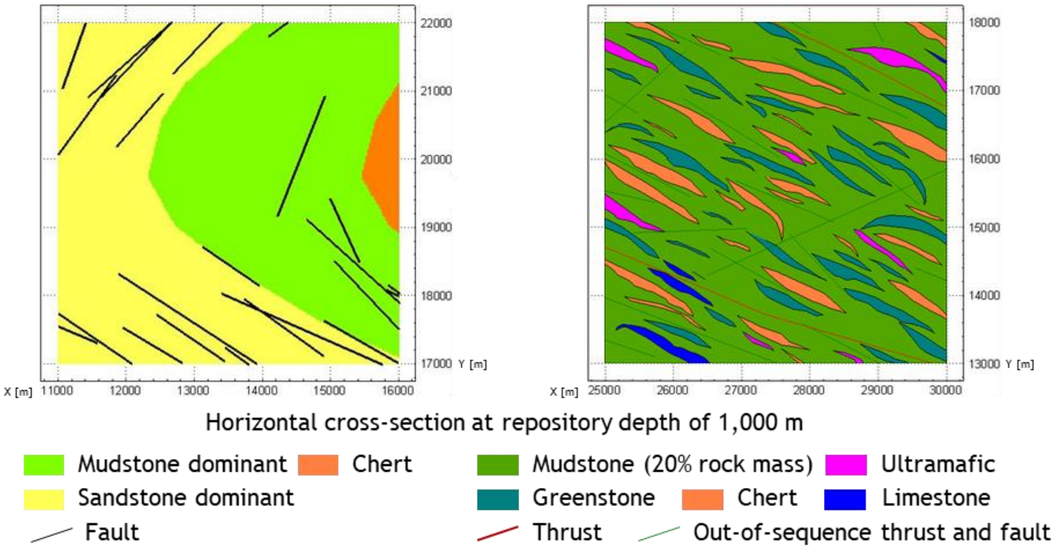

Figure 3.3-40 Repository scale geological models for Pre-Neogene sediments
Left: Coherent facies model, right: Mélange facies model

The repository scale hydrogeological model is the same as that used at a regional scale. The heterogeneity of the hydraulic properties of the coherent facies is clearly greater than that of the mélange facies, making it easier to identify issues related to engineering feasibility and post-closure safety of the repository, and hence this is selected as the reference case.

Table 3.3-12 shows the hydraulic parameters used the coherent facies and the resulting hydrogeological model is shown in Figure 3.3-41.

Table 3.3-12 Hydraulic parameters used for Pre-Neogene sediments

Hydrogeological units	Hydraulic conductivity (m/s)	Remarks
Faults and fractures	1.0×10^{-8}	> 1 km in length
Sediment	2.0×10^{-9}	Sandstone dominant and mudstone dominant formations are identical
Rock mass	1.0×10^{-8}	Chert

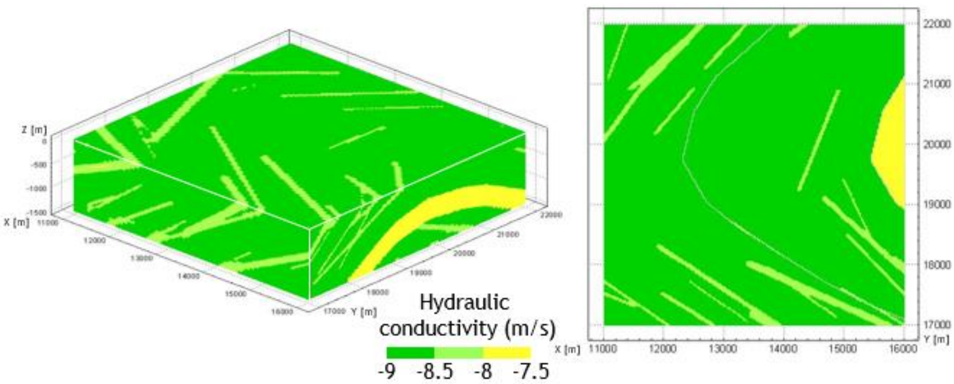

Figure 3.3-41 Repository scale SDM for Pre-Neogene sediments
Coherent facies, right: 3D model, left: Horizontal cross-section at a depth of 1000 m

The groundwater flow analysis at a repository scale again imposed fixed hydraulic heads at the boundaries based on the regional scale groundwater flow analysis (Figure 3.3-24). The resulting Darcy flux distribution at a depth of 1000 m is shown in Figure 3.3-42 while Figure

3.3-43 shows the distribution of the relative groundwater travel time for a distance of 500 m (for details, see Section 4.5.4 (1)).

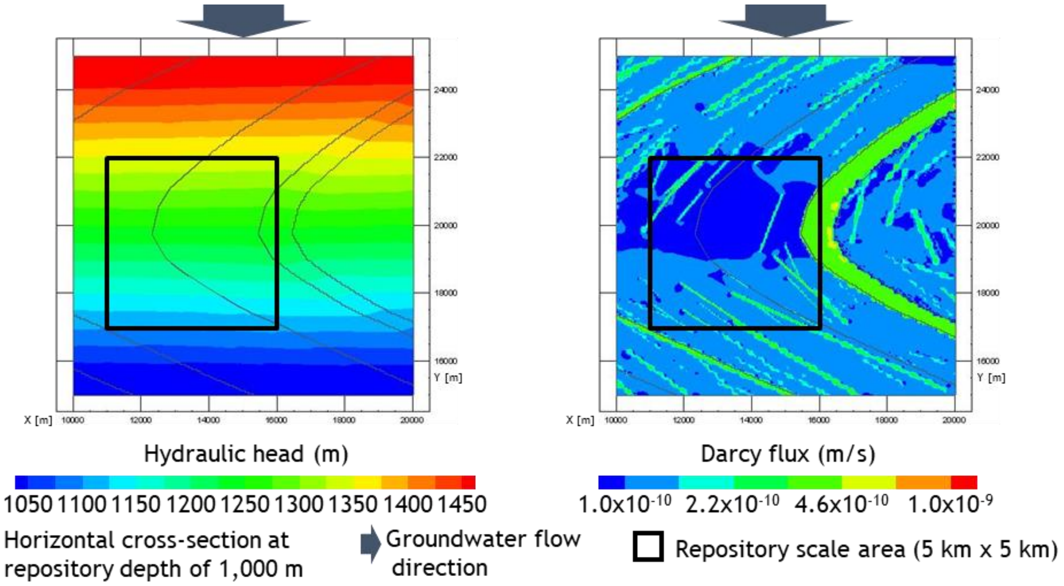

Figure 3.3-42 Head and Darcy flux distributions at the repository scale for Pre-Neogene sediments. Coherent facies, left: head distribution, right: Darcy flux distribution

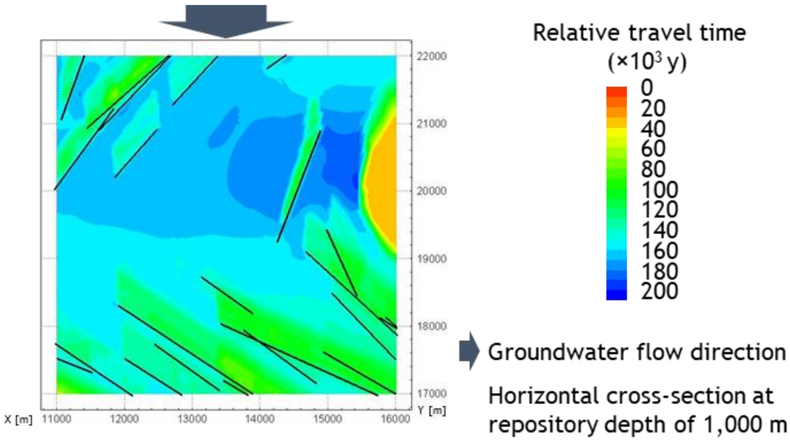

Figure 3.3-43 Relative groundwater travel time distribution for Pre-Neogene sediments on the repository scale

The results show that groundwater travel times tend to be shorter in the vicinity/upstream of the faults and chert rock blocks. The details of the development of the repository scale geological and hydrogeological models as well as the groundwater flow analyses for Pre-Neogene sediments is provided in Supporting Report 3-25.

(iii) Panel scale

(a) Plutonic rocks

The panel scale geological model was developed following the concept given in Section (3) (i) (a), using the same statistical data on faults and fractures (see Table 3.3-3, Figure 3.3-8) as for the regional and repository scale geological models. In particular, for faults and fractures shorter than 1 km, assuming a minimum length that could be determined from boreholes is 1 m, their volumetric density was determined based on one-dimensional density and inclination data from borehole wall observations [207].

The panel scale hydrogeological model was developed using transmissivity values obtained from a series of hydraulic tests lengths of 10 m or less at depths of 500 m or more, conducted in the Mizunami URL programme [213] [214]. In particular, the logarithmic mean and standard deviation of the transmissivity distribution were first tentatively assigned to faults and fractures modelled at a panel scale, with simulated results then compared with measurements [213] [214] for multiple DFM realisations. The transmissivity distribution that best described observations was then selected.

The hydraulic parameters used for developing the panel scale geological and hydrogeological models are provided in Table 3.3-13 and the resultant the panel scale models shown in Figures 3.3-44 and 45, respectively.

Table 3.3-13 Hydraulic parameters used for panel scale geological and hydrogeological models of plutonic rocks

Fault/fracture set	**Orientation**			**Length**	**3D density (m^2/m^3)**	**Transmissivity and distribution**
	Dip azimuth (°)	Dip angle (°)	Fisher coefficient	Power law exponent value Minimum length (m) Maximum length (m)		Logarithmic mean (m^2/s) Logarithmic standard deviation
1 (EW trending)	171	85	7.8	4.0 1 1,000	1.9	1.0×10^{-9} 2.0
2 (NS-trending)	80	87	7.5		1.4	
3 (low angle)	203	1	8.4		0.5	

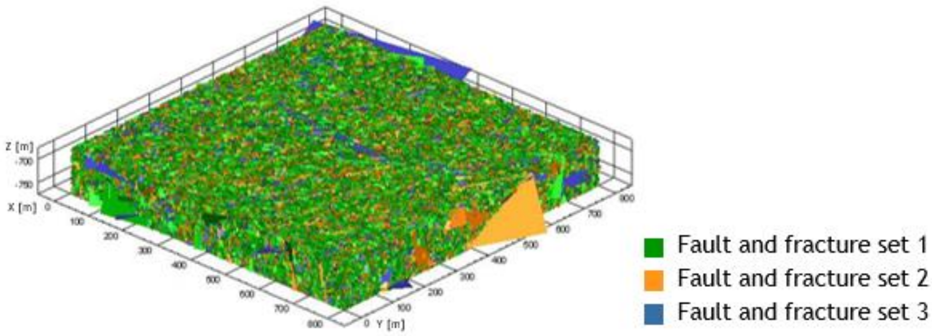

Figure 3.3-44 Panel scale geological model of plutonic rocks

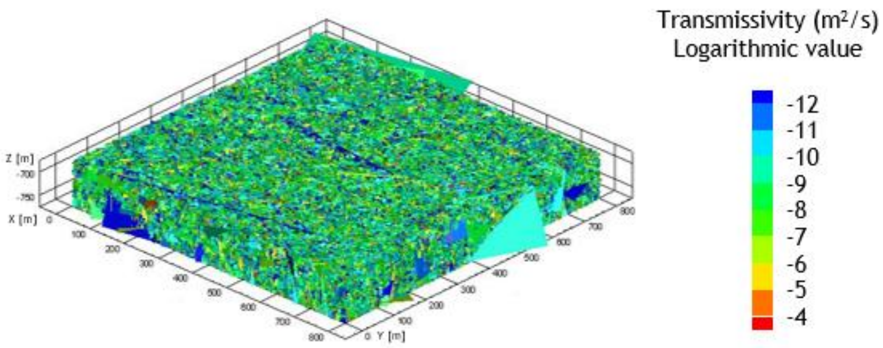

Figure 3.3-45 Panel scale hydrogeological model of plutonic rocks

The details of the development of the panel scale models are provided in Supporting Report 3-26.

(b) Neogene sediments

The panel scale geological model was developed for an arbitrary area of mudstone layers with relatively low hydraulic conductivity in order to assess issues related to post-closure safety. In particular, a case study [74] showed that the orientation, length and density of fractures differ depending on the timing and environment of formation, mineral composition, physical and mechanical properties of the mudstone. Thus, different sets of faults and fractures were generated for the upper and lower mudstone layers. Faults and fractures less than 1 km in length were modelled stochastically by applying a power law model (Figure 3.3-14) similar to that used for the regional and repository scale geological model.

The panel scale hydrogeological model describes the spatial heterogeneity of hydraulic properties of both the mudstone matrix and fractures. The transmissivity values of fractures were determined based on the results of borehole investigations carried out in the Horonobe URL programme [74]. The parameters used for developing the panel scale model are provided in Table 3.3-14, while resultant geological and hydrogeological models are illustrated in Figures 3.3-46 and 47, respectively.

Table 3.3-14 Parameters used for panel scale geological and hydrogeological models of Neogene sediments

Fault/fracture set		**Orientation**			**Length**	**3D density (m^2/m^3)**	**Transmissivity and distribution**
		Dip azimuth (°)	Dip angle (°)	Fisher coefficient	Power law exponent value Min length (m) Max length (m)		Logarithmic mean (m^2/s) Logarithmic standard deviation
Upper Mudstone Formation	1	323	52	9.8	3.3 0.15 1,000	0.53	1.1×10^{-8} 0.43
	2	203	42	52		0.06	
	3	118	11	3.1		0.44	
Lower mudstone layer	1	341	57	16	3.3 0.15 1,000	0.63	7.8×10^{-8} 0.52
	2	215	34	20		0.26	
	3	69	26	51		0.22	
	4	227	12	3.1		0.79	

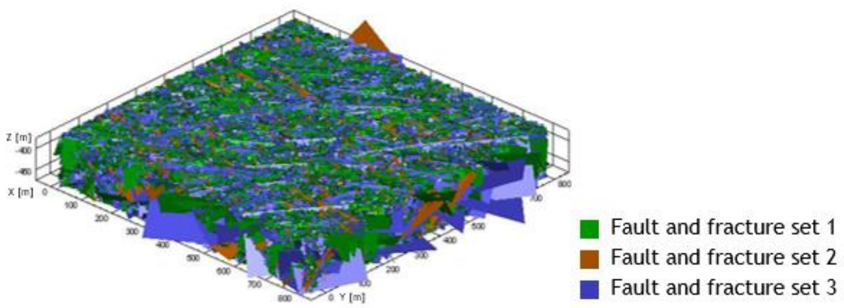

Figure 3.3-46 Panel scale geological model of Neogene sediments Fault/fracture distribution in the upper mudstone layers

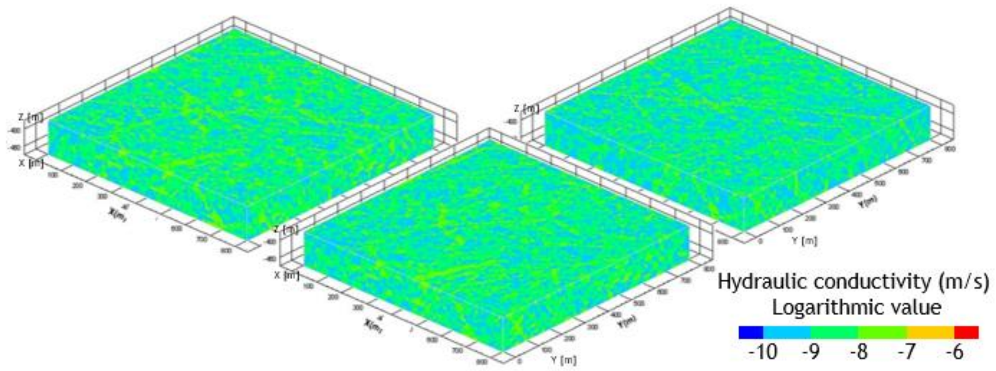

Figure 3.3-47 Panel scale hydrogeological model of Neogene sediments
Hydraulic conductivity distribution, Left: Horizontal (X) direction, Middle: Vertical (Z) direction. Right: Horizontal (Y) direction

The details of the development of the panel scale models of Neogene sediments is provided in Supporting Report 3-27.

(c) Pre-Neogene sediments

The panel scale geological model was developed using the same concept as that for plutonic rocks, with faults and fractures <1 km in length modelled using a power law based on the results of the fault/fracture length measurements [205] from tunnel wall observations in Japan. The panel scale hydrogeological model was developed based on the hydraulic conductivity and density of water-conducting features used in the repository scale hydrogeological model. The parameters used for developing the panel scale model are provided in Table 3.3-15.

Table 3.3-15 Parameters used for panel scale geological and hydrogeological models of Pre-Neogene sediments

Fault/fracture set	**Orientation**			**Length**	**3D density (m^2/m^3)**	**Transmissivity and distribution**
	Dip azimuth (°)	Dip angle (°)	Fisher coefficient	Power law exponent value Min length (m) Max length (m)		Logarithmic mean (m^2/s) Logarithmic standard deviation
1 (NE-trending)	358	76	20	4.0 0.15 1,000	12.5	2.0×10^{-9} 1.0
2 (NW-trending)	96	78	20		1.25	
3 (low angle)	223	19	20		1.25	

These parameters were used for both coherent and mélange facies. Following the discussion in Section (4) (ii) (c), modelling at the panel scale was carried out for the coherent facies. Examples of the resultant panel scale geological and hydrogeological models are shown in Figures 3.3-48 and 49, respectively.

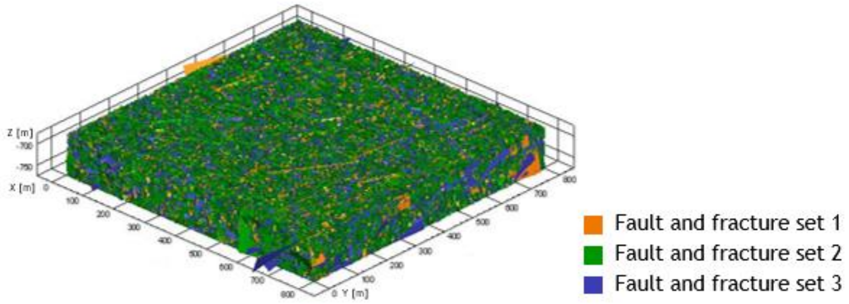

Figure 3.3-48 Constructed panel scale geological model of Pre-Neogene sediments Fault/fracture distribution for coherent facies

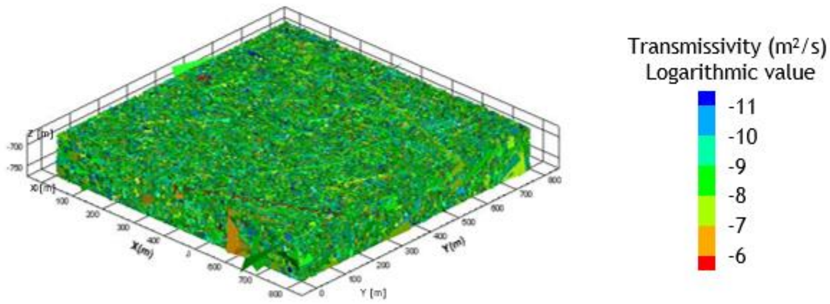

Figure 3.3-49 Constructed panel scale hydrogeological model of Pre-Neogene sediments Coherent facies

The details of the development of the panel scale geological and hydrogeological models for Pre-Neogene sediments is provided in Supporting Report 3-28.

(5) Conceptual modelling of water-conducting microstructure

For each of the representative host rocks, based on geological environment investigations and in-situ tests, a conceptual model was constructed to describe the characteristics of water-conducting microstructures that control radionuclide migration/retardation on a scale of a few cm to several tens of cm, as required for assessing post-closure safety (see Section 7.2.1 (2) (ii) (c) for further details). It can be noted here however that "flowing porosity" from such models will allow Darcy fluxes to be converted into transport times, that can then be used for the purposes of comparison with those calculated in previous sections.

(i) Plutonic rocks

Granites are taken as representative of plutonic rocks, allowing transfer of the results of natural analogue studies and in-situ tests conducted by JAEA at the Kamaishi mine [176] [215] [216]. Analysis of water-conducting fractures shows that advective flow occurs in a network of flow channels formed within fracture infill. It has also been confirmed that a network of interconnected pores exists in the fracture filling layer and the rock matrix (which has been altered), allowing solute diffusion into this material from the flow channels.

Taking these findings into account, a conceptual model of water-conducting microstructure in plutonic rocks is derived, as shown in Figure 3.3-50.

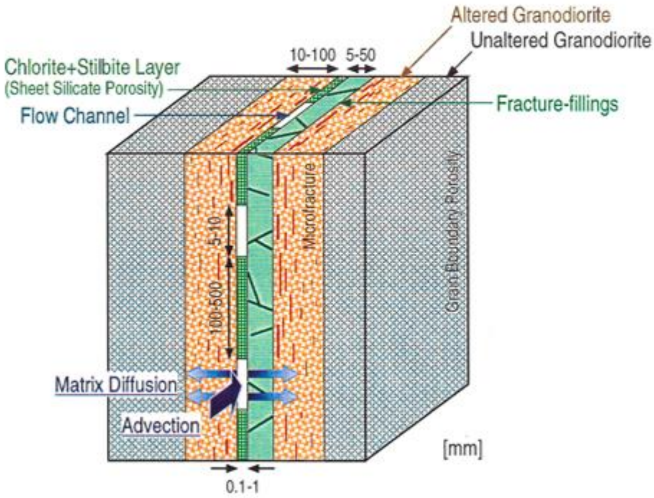

Figure 3.3-50 Conceptual model of water-conducting microstructures in plutonic rocks (Ota et al., 1999 [216])

In addition, based on a dual porosity model [217], migration and retardation of radionuclides in the water-conducting microstructure were conceptualised. The details of the modelling procedure are provided in Supporting Report 3-29.

(ii) Neogene sediments

Based on the findings from the Horonobe URL programme and the geoscientific research at the Tono mine [218] [219] [220], faults and fractures are known to be infilled with clay and rock fragments originating from the host rock, and contain a network of flow channels. This infill lies within a micro-fractured crushed structure (damage zone). Like plutonic rocks, it is considered that advection occurs predominantly in flow channels in the water-conducting fractures, with solute diffusion through the damage zone and into the rock matrix. As shown in Table 3.3-1, the large porosity and the developed network of connected pores in the matrix allows also groundwater flow to some extent in the matrix.

The resulting conceptual model, illustrated in Figure 3.3-51, defines the key migration scale features for Neogene sediments, which allows for dual permeability [217] migration of radionuclides in both channels and rock matrix. For details, see Supporting Report 3-30.

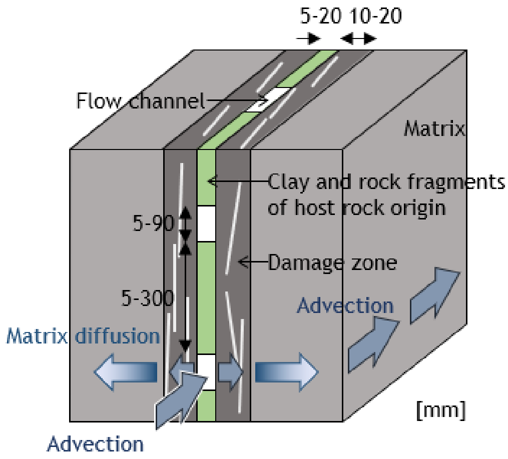

Figure 3.3-51 Conceptual model of the water-conducting microstructure for Neogene sediments

(iii) Pre-Neogene sediments

In Pre-Neogene sediments, based on analyses of water-conducting fractures in core samples [221], faults and fractures are known to be filled with calcite and clay minerals in which a network of flow channels occurs. As shown in Supporting Report 3-28 and Table 3.3-15, considering that the density of water-conducting fractures is high and their hydraulic conductivity is higher than that of the matrix, as for plutonic rocks it is assumed that advection occurs predominantly in the flow channels of water-conducting fractures, with solute diffusion from these into the fracture-filling mineral layer and the rock matrix.

Thus, the conceptual model shown in Figure 3.3-52 illustrates the water-conducting microstructure of Pre-Neogene sediments.

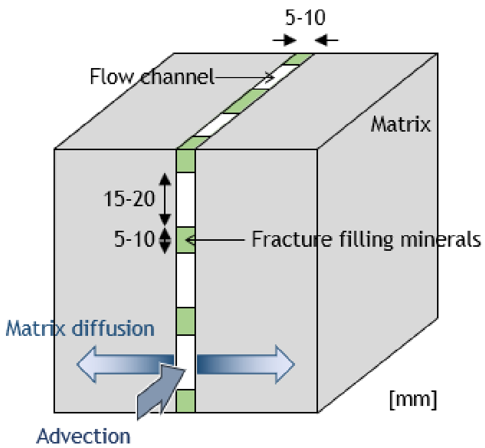

Figure 3.3-52 Conceptual model of the water-conducting microstructure for Pre-Neogene sediments (the porosity and matrix permeability of these rocks is similar to that of plutonic rock, thus advective flow in the matrix was not considered)

In addition, based on the dual porosity model [217], the migration and retardation of radionuclides in the water-conducting microstructure is conceptually shown. For details, see Supporting Report 3-31.

(6) Modelling groundwater chemistry

For each representative host rock, a model of associated groundwater chemistry is required for repository design (see Section 4.4 for details) and assessment of post-closure safety (see Sections 6.1 to 6.5 for details).

Groundwater chemical data are generally obtained through sampling in boreholes, and can be significantly affected by disturbances caused by both drilling (e.g. contamination due to the drilling fluid) and sample collection/analysis (e.g. degassing and oxidation). Particularly for assessing post-closure safety, it is essential to use groundwater chemical datasets of guaranteed quality, with effects of perturbations avoided to the extent possible. Based on this, available groundwater chemical data were first screened, using the procedure for quality assurance implemented for the Horonobe URL programme [222] [223]. For the groundwater in potentially suitable host rocks, where long term stability is expected, representative water chemistry datasets were then modelled to check for the above-mentioned disturbances. Here it was assumed that water chemistry is determined by chemical equilibration processes with the minerals existing in the water-conducting channels, allowing consistency of observed data to be assessed (even though disequilibrium is commonly observed in many deep groundwater systems, especially in terms of redox).

The established representative water chemistry datasets were assumed to apply to the entire host rock, thus spatial variations in chemistry were not considered. Only limited information on colloids, organic matter and microorganisms in groundwater is available from the JAEA URL programme [224] [225] [226] [227] [228] and thus, because potential impacts on radionuclide migration are sensitive to the hydro-geochemical setting, these factors were not considered further at the present stage at which no site has been identified.

Figure 3.3-53 summarises the procedure for determining representative groundwater chemical datasets, with further details in Supporting Report 3-32.

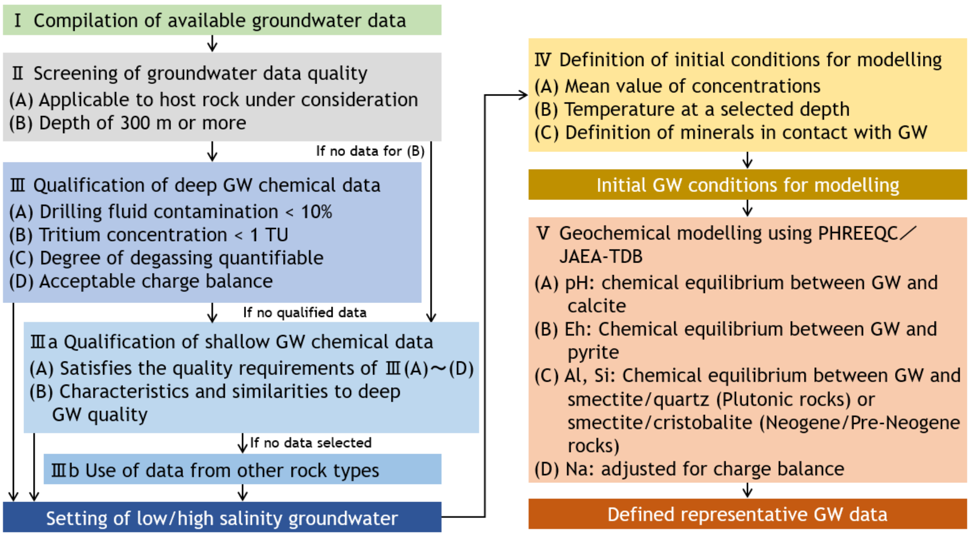

Figure 3.3-53 Processes for determining representative groundwater chemistry datasets for representative host rocks

(i) Acquisition and screening of groundwater chemical data

In addition to the nationwide groundwater chemical database [229], additional data were compiled from resource exploration and hot spring surveys conducted all over Japan; JAEA's

URL programme [74] [92]; the Kamaishi in-situ Test site [176]; and the Yokosuka demonstration project [78] (I in Figure 3.3-53). The references used are summarised in Supporting Report 3-32.

For the collected groundwater chemical data, the rock type was first identified from information on the groundwater sampling locations and depths. The data were then screened from the viewpoint of including only the three considered host rocks, as well as representing depths of 300 m or more (II in Figure 3.3-53). Further screening was then carried out to assure required data quality (III in Figure 3.3-53). Specifically, groundwater chemical data were selected based on (A) contamination by drilling fluid less than 10 %, (B) tritium in the groundwater less than 1 TU (tritium unit) indicating negligible contamination by drilling fluid or surface water, (C) data allows determination that any increase in pH or changes in chemistry due to degassing effects during sampling are small, (D) the charge balance of cations and anions conforms to the analysis guidelines [230], and thus the analysed values can be confirmed to be reliable.

As a result, as shown in Figure 3.3-54, chemical data for groundwater with low and high salinities for plutonic rocks and high salinity groundwater for Neogene sediments were compiled. For groundwater with low salinity in Neogene sediments and data for Pre-Neogene sediments, however, water chemistry data failed to meet the above-mentioned requirements (A) ~ (D), predominantly due to a lack of information to assess the degree of contamination by drilling fluid.

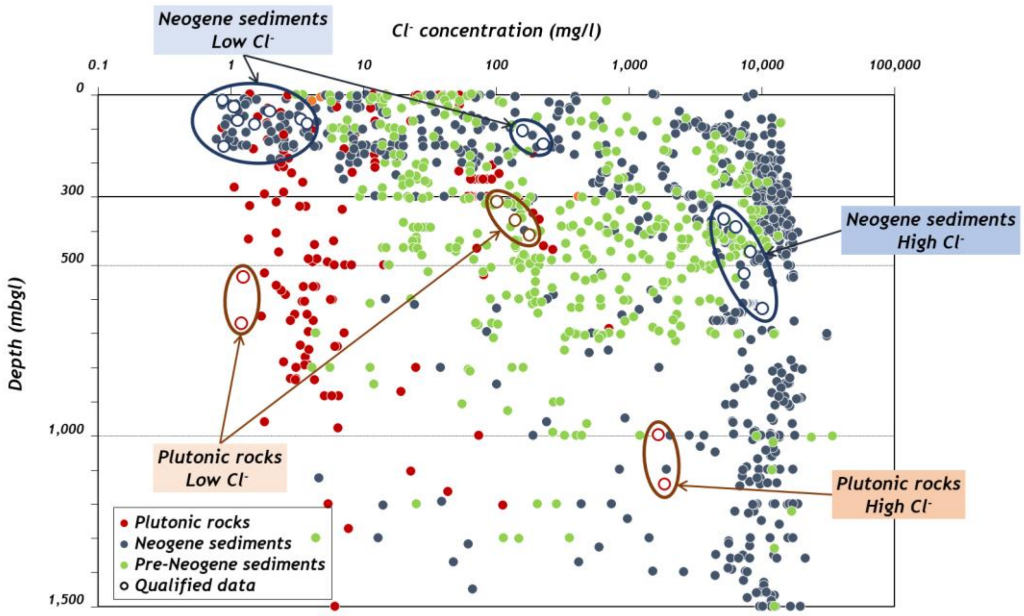

Figure 3.3-54 Selection of groundwater chemistry data for geochemical modelling

As shown in Figure 3.3-54, qualified low salinity groundwater chemical data for shallower Neogene sediments were then considered. Such groundwaters have long residence times in the formation, and have features that meet geochemical requirements such as being neutral to weakly alkaline, chemically reducing and with low carbonate concentrations (see Table 3.1-2) [79] [80]. As groundwater with a low salinity also exists within Neogene sediments deeper than 300 m, selection of the shallower water appears justified (IIIa in Figure 3.3-53).

For Pre-Neogene sediments, even shallower groundwater chemical data satisfying quality requirements could not be found. Therefore, considering that Neogene and Pre-Neogene sediments have similar ranges of groundwater chemistry (e.g. in terms of salinity) and the minerals present in the target mudstones, the water chemistry data selected for Neogene sediments were also used here (IIIb in Figure 3.3-53).

(ii) Initial conditions for geochemical modelling

Initially, for each rock, the initial groundwater chemistry was defined (IV in Figure 3.3-53) from selected data with both low and high salinities, and consideration of the ambient temperature at repository depth, minerals in the water-conducting channels that are expected to be in chemical equilibrium with groundwater and chemical components considered important from the viewpoint of safety assessment [231] [232].

The initial pH and concentrations of Na, K, Mg, Ca, total Fe, Al, F, Cl, Br, I, total S (calculated from the values of S^{2-}, HS^-, SO_4^{2-}), total P, total N (calculated from the values of NH_4^+, NO_3^-, NO_2^-), total inorganic C (TIC), Si, and B were determined by taking the arithmetic mean of available data. For temperatures, an average Japanese geothermal gradient of 3 °C/100 m and surface temperature of 15 °C, result in 45 °C for plutonic and Pre-Neogene sediments (repository depth 1,000 m), and 30 °C for Neogene sediments (repository depth 500 m). For granites, considered typical of plutonic rocks, calcite, iron hydroxide, pyrite, smectite, sericite, chlorite and quartz were selected as the minerals that are expected to be in chemical equilibrium with the groundwater in water-conducting fractures [82] [83] [92] [116] [216]. For Neogene sediments, based on the observations of target mudstones [74] [233] [234], calcite, dolomite, siderite, pyrite, smectite, illite, kaolinite, chlorite, zeolite, amorphous silica, cristobalite, quartz, and plagioclase were selected. The same set of minerals was used also for Pre-Neogene mudstone.

(iii) Representative groundwater chemistry

Geochemical modelling was carried out using PHREEQC ver. 3.0 [235] with thermodynamic database JAEA β-TDB ver. 1.07[236]. As noted in Figure 3.3-53 VI, the pH-Eh conditions for groundwater were first determined, considering the defined reference temperature of each rock. The concentrations of Al and Si, which tend to be overestimated in analyses due to the influence of colloids [237] [238], were determined next by assuming chemical equilibrium with relevant minerals and then charge was balanced.

In detail, pH was determined from CO_2 gas partial pressure and TIC concentration, assuming equilibrium between groundwater and calcite. Eh was then determined assuming chemical equilibrium between the groundwater and pyrite, while assessing consistency with in-situ Eh measurements included for some groundwater chemical data. The concentrations of Al and Si for plutonic rocks were determined assuming chemical equilibrium between the groundwater and smectite/quartz. For Neogene and Pre-Neogene sediments, Al and Si concentrations were determined assuming chemical equilibrium between groundwater and smectite/cristobalite. Finally, the representative groundwater chemistry was determined by correcting the charge balance resulting from the above chemical equilibrium calculations with Na, the highest concentration cation in the groundwater.

The representative groundwater chemistry for each rock is summarised in Table 3.3-16.

Table 3.3-16 Groundwater chemistry for representative host rocks

Host rock		Plutonic		Neogene		Pre-Neogene	
Groundwater		Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
T	(°C)	45	45	30	30	45	45
pH	(-)	8.16	7.56	8.38	6.54	8.15	6.33
Eh	(mV)	-301	-259	-282	-168	-289	-171
Na	(mol/l)	3.09×10^{-3}	1.72×10^{-2}	2.77×10^{-3}	2.18×10^{-1}	2.82×10^{-3}	2.19×10^{-1}
K	(mol/l)	1.58×10^{-5}	1.02×10^{-4}	3.01×10^{-5}	3.18×10^{-3}	3.01×10^{-5}	3.18×10^{-3}
Mg	(mol/l)	8.23×10^{-6}	6.17×10^{-5}	1.47×10^{-5}	4.95×10^{-3}	1.47×10^{-5}	4.95×10^{-3}
Ca	(mol/l)	3.96×10^{-4}	1.60×10^{-2}	2.26×10^{-4}	3.45×10^{-3}	2.26×10^{-4}	3.45×10^{-3}
Total Fe	(mol/l)	8.95×10^{-7}	4.92×10^{-7}	8.45×10^{-7}	3.25×10^{-5}	8.45×10^{-7}	3.25×10^{-5}
Al	(mol/l)	7.91×10^{-7}	2.84×10^{-7}	2.20×10^{-8}	1.31×10^{-9}	4.25×10^{-8}	2.44×10^{-9}
F	(mol/l)	5.68×10^{-4}	1.26×10^{-4}	1.90×10^{-4}	6.49×10^{-6}	1.90×10^{-4}	6.49×10^{-6}
Cl	(mol/l)	2.34×10^{-3}	4.90×10^{-2}	1.11×10^{-3}	2.08×10^{-1}	1.11×10^{-3}	2.08×10^{-1}
Br	(mol/l)	4.32×10^{-6}	3.88×10^{-5}	4.44×10^{-6}	7.98×10^{-4}	4.44×10^{-6}	7.98×10^{-4}
I	(mol/l)	7.88×10^{-6}	5.52×10^{-6}	3.94×10^{-6}	1.83×10^{-4}	3.94×10^{-6}	1.83×10^{-4}
Total S	(mol/l)	7.28×10^{-6}	2.03×10^{-5}	1.24×10^{-4}	4.09×10^{-6}	1.24×10^{-4}	4.09×10^{-6}
Total P	(mol/l)	6.46×10^{-7}	5.26×10^{-6}	5.62×10^{-6}	5.92×10^{-6}	5.62×10^{-6}	5.92×10^{-6}
Total N	(mol/l)	2.03×10^{-5}	2.77×10^{-5}	2.54×10^{-6}	1.01×10^{-2}	2.54×10^{-6}	1.01×10^{-2}
Total C	(mol/l)	9.48×10^{-4}	2.16×10^{-4}	1.66×10^{-3}	4.00×10^{-2}	1.70×10^{-3}	4.66×10^{-2}
Si	(mol/l)	3.20×10^{-4}	3.05×10^{-4}	7.47×10^{-4}	6.64×10^{-4}	1.03×10^{-3}	9.18×10^{-4}
B	(mol/l)	4.62×10^{-6}	2.73×10^{-4}	4.62×10^{-6}	1.02×10^{-2}	4.62×10^{-6}	1.02×10^{-2}
Ionic strength	(mol/l)	0.004	0.065	0.004	0.238	0.004	0.238

The representative groundwater chemistry datasets for low and high salinities as defined bound the ranges of deep groundwater compositions in Japan for these rocks. Furthermore, pH values are neutral to weakly alkaline and waters are reducing, which meets the requirements for a suitable geological environment after closure (as shown in Table 3.1-2). In addition, when defining this chemistry, geochemical modelling allows correction to the specified ambient rock temperature. Such modelling of reference groundwaters, and also correction of temperature-dependent data obtained from laboratory experiments, involves uncertainties that will need to be better defined in the future.

(7) Rock thermal and mechanical properties

For each rock, information collected on a nationwide scale is utilised to define thermal and mechanical properties required for repository design (see Section 4.5.4 (1) for details) and post-closure safety assessment (see Sections 6.4.1 (2) and (4) for details).

In particular, average and median values for thermal conductivity, effective porosity and unconfined compressive strength were defined as representative values for each rock, based on the data presented in the H12 report [7] and complemented by more recent measurements.

To quantify the variability of the complied thermal and mechanical data, first and third quartile values were also shown.

For Neogene sediments, the SDM assessment leads to selection of the upper mudstone layer as the repository host rock (e.g. Figures 3.3-34 and 3.3-38) and therefore thermal conductivity and unconfined compressive strength required for design studies are defined for this formation. The effective porosity is required for the evaluation of migration and retardation of radionuclides and thus averaged over all rock types. Similarly, for Pre-Neogene sediments, the thermal conductivity and unconfined compressive strength were specified for mudstone and sandstone, while the effective porosity was averaged over all rock types. For Pre-Neogene sediments, the selected reference is coherent facies, as discussed in Section (4) (ii) (c). It was, however, difficult to judge from the literature information whether mudstone data reported corresponds to coherent facies or not, and hence no distinction was made between coherent and mélange facies.

The thermal and mechanical property datasets are shown in Table 3.3-17. The statistical distribution of the compiled thermal and mechanical property data together with the references used are summarised in Supporting Report 3-33.

Table 3.3-17 Thermal and mechanical property datasets for representative host rocks

Parameter		Plutonic	Neogene sediments	Pre-Neogene sediments
Thermal conductivity (W/m K)	Number of data	113	52	30
	Mean value	2.9	1.6	1.7
	Median	2.8	1.6	1.9
	3rd quartile	3.0	2.0	2.2
	1st quartile	1.9	1.0	1.4
Effective porosity (%)	Number of data	1,647	1,230	420
	Mean value	1.5	27	6.8
	Median	0.8	25	3.5
	3rd quartile	1.1	39	10
	1st quartile	0.5	13	1.4
Uniaxial compressive strength (MPa)	Number of data	805	1,057	592
	Mean value	110	24	88
	Median	108	6	68
	3rd quartile	165	20	142
	1st quartile	57	3	18

The values for thermal conductivity and uniaxial compressive strength for Neogene and Pre-Neogene sediments in the table were defined for specific lithofacies as described above. Therefore, these values are not necessarily identical to the representative values in Table 3.3-1, which did not specify lithofacies.

3.4 Probability of occurrence and impacts of natural perturbing phenomena

In this report, as will be described in Section 6.1.5 (1), NUMO assess the possible impact of natural perturbations on post-closure safety (see Section 6.4.3 for details). This is based on a risk assessment, with decoupled consideration of the probability of occurrence of selected scenarios (see Section 6.3.2 (3) for details) and quantitative analysis of consequences (see Section 6.3.3 (3) for details). As previously discussed, significant impacts of such phenomena should be avoided to the extent possible through the staged site investigation process. However, it is important to consider these, even if they have a very low probability of occurrence and/or could occur only in the distant future, in order to assess if they could have a significant impact on the safety of the repository. The scientific understanding of relevant phenomena, as required for safety assessment, is summarised below.

Inflow of volcanic hydrothermal fluids and deep-seated fluids is not described here because the scientific knowledge necessary to assess the likelihoods and consequences of this process is not considered sufficient at this stage.

3.4.1 Volcanic/igneous activity

Magma intrusion into, and eruption through, a repository could clearly impact post-closure safety of even a properly sited and designed facility [1], even if only occurring in the far future. As stated in Sections 3.2.2 (1) and (2), even in areas where volcanic and igneous activity are not presently evident, NUMO excludes areas where significant volcanic and igneous activity is expected to occur over the coming tens of ky.

As discussed in Section 3.1.3 (1) (i), locations of volcanic fronts in Japan are determined by subduction of tectonic plates and have not significantly changed over a long period of time, with volcanic activities repeatedly occurring in the back-arc regions of these fronts [16] [26]. According to the Quaternary volcano distribution map [20] [21], it can be confirmed that volcanic and igneous activity is very unevenly distributed and has not occurred in the fore-arc region of the volcanic front in Tohoku, as well as the Shikoku region, for at least several My. Volcanoes are also unevenly distributed in the back-arc region of the front, with regions of high and no volcanic activity clearly distinguished [26].

From the viewpoint of long-term stability of magma supply systems, areas with an extremely low probability of volcano formation over the next 100 ky can be identified, especially in the fore-arc region of the volcanic front [239]. In the back-arc region of the volcanic front in Tohoku, however, cases of new volcano occurrence have been identified, even when there was no record of volcanic activity during last several 100 ky [16] [240] [241].

For any particular location, the probability of volcanic activity as a function of time over the next 100 ky has been evaluated stochastically using such as the ITM-TOPAZ method described in Section 3.2.3 (2) [143] [167] [169] [170] [171] [172] [239]. Relevant scientific knowledge to allow assessment of magma intrusion into the repository and eruption at the surface is summarised in Supporting Report 3-34.

3.4.2 Earthquake and fault activity

As fault movement could cause displacement within the repository or significant changes in hydrogeology, the impacts on post-closure safety need to be assessed, given that this cannot be precluded even for a properly sited facility [1]. Although the significance may be exaggerated for real cases, a special concern is identified as faults extending from repository depth to the surface. Fault investigations are conducted using an interdisciplinary approach across various fields, such as geomorphology and geology. In this section, NUMO adopts the fault definitions of the Japan Nuclear Safety Institute (2013) [242].

In the Japanese archipelago, as discussed in Section 3.1.3 (1) (iii), faults formed under earlier regional stress field may be reactivated, depending on the regional stress field during the Quaternary or local changes to this [33] [34] [35] [36] [49] [243]. Even in cases where the existence of faults cannot be confirmed at the surface [39], potentially active faults may still exist underground [26] and be reactivated due to evolution of the local stress field [48]. Therefore, potential impacts of this must be assessed, even for sites with no known active faults.

Although cases of such faults have been recorded for inland earthquakes of M6.5 or more [244], no quantitative information has been obtained on faults that extend to the surface from deep underground. Therefore, using the active fault database of Japan [41], the probability that a fault will appear on the surface in the future in the repository area was calculated for active faults [33] [34] [37] that are considered to have been repeatedly active in the Japanese archipelago for at least the past several 100 ky. The probability was calculated very simplistically by extrapolating the frequency of fault occurrence throughout Japan, assuming that faults appear on the surface due to a single fault movement that took place during the past 100 ky. The resulting probability of a future fault reaching the surface from deep underground in a repository area is on the order of 10^{-7}/y.

As stated in Section 3.3.3 (3) (i) (a), identified active faults with a length of ≈10 km could generate the equivalent of a M6.5 earthquake. In addition, there is a possibility of movement significantly affecting underground facilities [195] and hence they are excluded from the repository-scale area. However, faults 1 to 10 km in length may be included in repository-scale areas. Based on investigations at the Mizunami URL project [92], it was considered possible to roughly determine the position, structure and hydraulic characteristics of such faults by surface geophysics. In offshore areas, depending on the target geological setting, it may be difficult to identify faults by geophysical surveys with the same resolution as on land [69]. Combined with borehole surveys, however, it is possible to understand the distribution and properties of large-scale faults. Through such investigations, faults with a length of 1 to 10 km are avoided to the extent practical in panel-scale areas.

Regarding the hydraulic and mechanical effects of earthquakes and fault movements on the surrounding rock mass, scientific knowledge is limited, but there are cases where the permeability of the rock near a fault increased by about a factor of 5 immediately after fault movement and recovered to the original state several years later [245] [246]. There are also cases in which changes in permeability due to hydraulic fracturing, fluid rise/circulation were found in the vicinity of the fault plane (≈ several metres) [247] [248]. Changes in groundwater level due to changes in the volumetric strain of the rock mass were observed over a wide area in Japan following the extremely large Tohoku Earthquake and subsequent aftershocks [145] [249] [250]. These changes recovered to the original state at many locations within a year, and show that there are no significant effects on the long-term hydraulic gradient [251]. It has also been shown that enhanced groundwater outflows following the Tohoku Earthquake continued for more than four years in some cases [252]. In addition, various formulae based on the magnitude of the earthquake, length of the fault, width of the fault zone, width of the process zone, and the displacement of fault have been proposed [45] [253] [254] and their applicability in underground environments has been tested [115].

Changes in groundwater chemistry due to earthquake and fault activity are considered to be caused by mixing of groundwater of different origins, such as water rising from deeper underground [255] [256] [257] and drawn down oxidising surface water [258], as observed near fault zones. Chemical changes tend to be slower than changes in groundwater level or temperature [259]. The movement of groundwater near a fault is assumed to be caused by the opening and blockage of microcracks and changes in water-conducting features, due to mechanical changes from fault movements [256] [258]. In overseas studies [260] [261] [262], similar processes have been identified as factors causing short term (up to a few years) changes in groundwater chemistry due to fault activity. Following the Tohoku Earthquake, studies showed that changes in groundwater chemistry persisted for several months [116] [263], thought to have been caused by a temporary change in the mixing conditions of groundwaters with different chemistries, due to changes in hydrology following fluctuations in water pressure [116].

Relevant scientific understanding to assess impacts on a repository due to fault movement are summarised in Supporting Report 3-35.

3.4.3 Uplift and erosion

Over time, the repository may gradually approach the surface due to uplift and erosion and, even if only the thickness of overburden is reduced, the impact on post-closure safety of the repository needs to be assessed [1].

Both uplift and erosion are influenced by regional differences between inland and coastal areas; differences in topography and geology; differences of scale, speed and continuity of crustal movement; and periodic climate and sea-level changes [264]. As the time scale increases, the magnitude of the changes gradually increase from micro-topography (natural levees and valley bottom plains) to small size terrain features (fans and deltas) and medium sized terrain features (mountains and basins). Therefore, crustal changes are included within the different spatial scales in order to assess the topography constraining uplift/erosion [265] [266].

For most parts of Japan, changes in ground level result from the differences between the rates of uplift and erosion. For uplift, average regional rates over last 100 ky have been documented nationwide [26]. For times greater than 100 ky, the evolution of the plate tectonic setting needs to be considered. In the TOPAZ study (e.g. TR-16-04), a range of bounding scenarios for such evolution are described and their impact on the rate and consequences of uplift assessed.

For erosion, local models assess the correlation between terrain statistics (e.g., topographic gradient) and erosion rates [140] [267] [268] [269] [270]. In particular, using models that can treat erosion rate variability with time, erosion rates have been determined from the amount of dam sediment and the area of dam catchment over periods of several decades. It has been shown that there is a strong correlation between derived values and the topographic relief of the catchments [140] [267] [268] [269].

In Japan, topographic relief increases with altitude, and the erosion rate over timescales of decades tends to increase. Since topographic relief is defined with reference to sea-level [269], it is necessary to consider changes in erosion rate due to the effective change of elevation caused by sea-level changes. As noted in Section 3.1.3 (1) (iv), over the past ≈My, global glacial cycles have a duration of about 100 ky [63]. During glacial periods, precipitation decreases along with a decrease in air temperature and, in mountainous areas, net erosion may also decrease (glaciation is not significant for most of Japan). On the other hand, downward erosion advances in coastal areas as the supply of sediment from upstream decreases and the sea-level drops. The opposite occurs during interglacial periods.

For many parts of Japan, except for areas such as active fold zones within the strain concentration zone, the uplift rate for the last 100 ky [26], the uplift rate over millions of years [139] [264] [271] [272] [273] and the rate of change in topographic gradient [273] can be confirmed to show very similar trends.

In order to evaluate potential impacts on post-closure safety, available scientific knowledge on uplift and erosion rates has been collated and is summarised in Supporting Report 3-36. Because this requires consequence analysis of scenarios describing the coupled evolution of the EBS and the geological setting over periods > 100 ky, such assessment is not included in the current safety case due to limitations of the existing toolkit. However, developing the required time-dependent models and databases is identified as a priority for the future.

3.5 Summary and future perspective

3.5.1 Summary

In this chapter, advances made since H12 in the basic concept for selecting a stable geological environment suitable for radioactive waste disposal as well as in the required site investigation technology were summarised. Based on the latest scientific knowledge, suitable geological environments were identified in plutonic rocks and Neogene plus Pre-Neogene sediments. To capture key characteristics of the geological setting, SDMs were constructed for each of these representative host rocks to serve as the basis for repository design and safety assessment.

NUMO, as the implementer of the geological disposal project in Japan, has developed the required technology and stepwise site selection plan for carrying out site investigations. NUMO has also developed approached for interpreting and integrating resulting geoscientific information into SDMs. By iterating synthesis of geological knowledge within the SDMs with use of these to focus associated repository design and safety assessment, NUMO has the technical basis that will allow transparent and technically-justified selection of favourable geological environments at a suitable site.

(1) Investigation and evaluation technology

Based on the latest scientific knowledge, deep geological environments with favourable long-term characteristics from the viewpoint of radioactive waste disposal are considered to be widely distributed in Japan. Although located in an active tectonic setting, it is possible to select suitable environments by avoiding sites with risks of significant natural perturbations, based on an understanding of their temporal and spatial distribution.

In particular through knowledge gained in JAEA's URL programme, the basic concept and required methodology was established for selecting suitable geological environments during the stepwise site selection process. At each stage of site selection, in terms of confirmation of statutory requirements and siting factors, investigation/evaluation items are identified to assure long-term stability, engineering feasibility of safe construction and operational / post-closure safety. The multidisciplinary geoscientific information obtained through site investigations will be assessed for consistency and integrated into SDMs. These illustrate the geological environment, including characteristics such as the geometry of the geological formations and structures present, their associated thermal/hydraulic/mechanical properties and the spatial distribution of groundwater chemistry. Based on these results, long-term evolution of the geological environment is also conceptually assessed and taken into account in site evaluation (captured within a 4D SDM). Factors related to the geological environment having significant effects on engineering feasibility and pre-/post-closure safety are identified, serving to focus subsequent site investigation to reduce uncertainties associated with them.

NUMO aims to utilise the best available characterisation technology, tailored to site-specific requirements and boundary conditions. Therefore, available technology has been reviewed to confirm its applicability, based on either an established track record in fields such as resource development or construction or as a result of research and development conducted by relevant research institutions. Especially for coastal areas, where there was little experience in relevant site investigation, advances have been made in technology for continuous determination of profiles of geological setting and groundwater characteristics from land to sea, as well as methods for modelling evolution of the geological environment as a result of Quaternary crustal deformation. Through the general acquisition and analysis of advances in geological knowledge, NUMO is working to strengthen the technical basis for conducting site investigations and evaluations for the diverse geological environments found in Japan.

In conjunction with the above efforts, NUMO has been developing approaches and methods for stochastically evaluating the likelihood of occurrence, impacts and uncertainties of natural perturbation phenomena for periods in excess of 100 ky. In addition, to support planning and implementation in an effective and efficient manner, documents describing basic concepts and application manuals that capture practical experience have been produced that cover both site investigation and associated quality management.

Thus, systematic development and demonstration of effective investigation and evaluation technologies for the diverse geological environments in Japan are steadily progressing. By applying these, NUMO will be able to identify the geological environments suitable for geological disposal through the future stepwise site selection processes.

(2) Modelling of representative host rocks

An approach of developing SDMs to integrate geoscientific information arising from investigations in the stepwise site selection process has been illustrated. In the absence of volunteer sites, representative SDMs serve as the basis to demonstrate capability to both design and carry out a safety assessment of a repository.

Considering the requirements and standards set by the Geological Disposal Technology WG, potential geological environments that may result from site selection were identified, focusing on currently identified characteristics important to determine engineering feasibility (constructability and ease of disposal) and post-closure safety (groundwater flow, nuclide migration/retardation). Plutonic rocks together with Neogene and Pre-Neogene sediments were selected as representative host rocks, while Neogene/Pre-Neogene volcanic and metamorphic rocks that may also come into consideration were confirmed to be covered by the assessments for plutonic rocks and Pre-Neogene sediments.

For each of the representative host rocks, the SDMs were constructed from available nationwide geoscientific information and that derived from JAEA's URL programme. Such SDMs capture the 3D geometry of the geological setting, the length/density/orientations of faults, fractures and other key structural elements together with their associated hydrogeological, physical and hydrochemical properties. Geological and hydrogeological models were developed as a nested set, including regional-scale (several tens of km × tens of km), repository-scale (5 km × 5 km), and panel-scale (800 m × 800 m) representations. Such development takes into account the fact that the quality and quantity of the geoscientific information will evolve as site investigations progress, thus the characteristics of the geological environment were modelled assuming that finer resolution of structures will be available as the requirement for smaller scale representations of the SDMs arises.

Furthermore, for each rock, models were constructed on a cm-dm scale to capture the characteristics of the water-conducting features that determine the migration and retardation of radionuclides. Required groundwater chemistry and thermal/mechanical property datasets for engineering and safety assessment were derived from available literature. In particular, Japanese groundwater chemistry data were screened in terms of rock type, sample depth, degree of contamination by drilling fluid and/or surface water, degree of degassing and charge balance. For groundwater chemistry data meeting quality requirements, representative datasets were determined on the basis of assumed equilibrium between groundwater and minerals present in water-conducting features. For each rock, the representative groundwater chemistry datasets with low and high salinity comprehensively cover the ranges of chemistry in deep groundwater in Japan.

Through the above efforts, the effectiveness of NUMO's technology for integrating the latest scientific knowledge on relevant geological environments, and capture of this within SDMs, has been demonstrated, providing a sound basis for the literature survey and subsequent siting stages. For Pre-Neogene sediments (especially accretionary complex) that have been little studied from the viewpoint of geological disposal, interpretation/integration of the limited geoscientific information available has confirmed that favourable hydraulic, mechanical and chemical conditions for geological disposal could be found in Japan.

3.5.2 Future perspective

Future issues that should be addressed have been identified by the government, NUMO and related research institutions; these are summarised in this report (e.g. Tables 3.2-2 and 3.2-3) as well as by the Advisory Committee for Natural Resources and Energy (2014) [1] and the WG on technical issues of geological disposal below the coastal seabed [159]. In all cases, particular emphasis was placed on rigour in conducting the preliminary investigations, although not all issues need to be resolved prior to that stage.

In order to select a suitable site in Japan, it is essential to improve the reliability of assessments of the occurrence and impacts of natural perturbing phenomena. Required understanding can be derived from case studies for large-scale areas and for time periods that are as long as possible. In particular, it is important to enhance scientific knowledge related to the flow of volcanic hydrothermal and deep-seated fluids, for which understanding is weak compared to other potential perturbations. Also assessment of land uplift and erosion will need more careful site-specific study. For the investigation and evaluation technologies required, the scope of application of new methods and combinations of them will be expanded and their effectiveness, accuracy and resolution confirmed through further case studies, allowing improvement of NUMO's characterisation toolkit.

It is also essential to improve reliability of the technology for characterising the geological setting of potentially suitable sites and its associated long-term evolution, providing the geoscientific information necessary for assessing engineering feasibility and post-closure safety of repository concept options. Borehole drilling and investigation techniques can be rationalised and optimised, particularly in terms of obtaining accurate geological information to meet these requirements, taking into account the diversity of geological environments in Japan. Rationalising/optimising borehole drilling and associated investigation technology will be focused by feedback from engineers and safety assessors, which will be facilitated by improved 4D SDMs that capture site evolution, including long-term changes in hydrogeological and geochemical characteristics that impact RN release and transport. Furthermore, specific technology for coastal areas will be enhanced, so that the completeness and quality of the resulting geoscientific knowledge base would be similar to that for land areas. All of this will be accompanied by improvement of the quality management system and strengthening of the technical basis for site investigations through capture of practical experience ("tacit knowledge").

These issues are, as discussed in Section 2.5, reflected in the Overall Plan for Geological Disposal R&D [274], which was compiled by the Geological Disposal Research and Development Coordination Council. Table 3.5-1 summarises future efforts in the areas of: occurrence and impacts of natural perturbations, geological characteristics and their long-term evolution and strengthening the technical basis for site investigations.

Table 3.5-1 Future topics for selection and modelling of suitable geological environments

Topic	What will be done
Occurrence and impacts of natural perturbations	• Advancement of technology for assessing the occurrence and impact of volcanic/igneous activity • Development of technology to improve understanding occurrence and impacts of movement of deep-seated fluids • Advancement of technology for assessing the occurrence and impact of earthquakes and fault activity • Advancement of uplift/erosion assessment technology based on topographical and geological information • Further development of stochastic methods to capture probabilities and consequences of rare phenomena, together with associated uncertainties
Determination of geological characteristics and their evolution	• Development of technology for determining hydraulic and solute transfer characteristics of water-conducting features • Based on potentially suitable repository concepts, assess how groundwater composition and its evolution may affect stability of the EBS • Development of investigation and evaluation technologies applicable under the coastal seabed • Advancement of models of long-term evolution of geological environmental characteristics • Development of borehole investigation/monitoring/sealing technologies
Strengthening the technical basis for site investigations	• Improvement of the scientific knowledge base on the occurrence and impacts of natural perturbations • Improvement of the scientific knowledge base on geological environmental characteristics and their long-term evolution • Expansion of the technical knowledge base on geological investigation and evaluation • Expansion of the quality management system • Accumulation of relevant practical experience

For these topics, NUMO will work together with government and relevant research institutions to implement a coordinated R&D programme to ensure that required methodology, technology and experience is available as and when required. This is discussed further in the following sections.

(1) Occurrence and impacts of natural perturbations

(i) Advanced technology for assessing the occurrence and impact of volcanic/igneous activity

To improve assessment of the potential for new volcanic and igneous activity and its resultant impacts, development of required technologies will provide a better understanding of the internal structure of the crust and mantle on a regional basis as well as the potential impacts depending on the type of volcanic activity (stratovolcanoes, calderas, or monogenetic volcanoes).

More specifically, investigations of underground structures linked to possible future volcanic activity will benefit from expanded seismic databases using teleseismic earthquakes, so that the distribution and movement of fluids in the crust and mantle can be studied up to a depth of several tens of kilometres. This will improve existing models for the generation and migration of magma. For calderas and monogentic volcanoes in particular, case studies to better understand the range of potential magma impacts will be conducted.

For coastal waters, investigation technology used to determine the presence and distribution of magma and other deep fluids on land (particularly seismic techniques) will be refined so that they can be applied offshore with the same level of accuracy and spatial resolution (applies also to (ii) below).

(ii) Development of technology to improve understanding occurrence and impacts of movement of deep-seated fluids

For non-volcanic deep-seated fluids (deep rising water and long-term stagnant water), understanding of phenomena related to formation and movement deep underground will be refined, and technologies for understanding the potential of flow from deep underground to the near surface will be developed.

The geological, geophysical and geochemical knowledge required to understand the formation mechanisms and distribution of deep fluids will be accumulated, together with geological environment characteristics related to fluid migration. Based on this, appropriate technologies to assess potential upwards flow of deep fluids along with associated thermal, hydraulic and geochemical effects will be developed.

(iii) Advanced technology for assessing the occurrence and impact of earthquakes and fault activity

To improve understanding of the hydraulic and mechanical impacts of fault activity, as well as identifying active faults without signatures at the surface or overlying formations, investigation technology will be further developed and approaches that combine several different methods assessed.

More specifically, to detect and characterise active faults without clear signatures, approaches that combine geodetic methods with topographic/geological assessments, geophysical surveys, and crustal deformation simulations will be extended. Based on establishing a history of geological structure development through examination and chemical analysis of minerals in fault zones, as well as the improvement in radiometric dating methods, evaluation approaches to assess reactivation of hidden faults will be developed. In addition, simulation techniques to evaluate the displacement of faults due to changes in the stress field, together with the range of the hydraulic and mechanical impacts in the vicinity of the fault, will be developed. Furthermore, by accumulating and analysing case studies on long-term changes in water pressure and chemistry of springs and groundwater following earthquakes, associated impacts on site properties will be investigated.

For coastal areas, especially for active faults extending from land to sea, technical information from case studies to improve the accuracy and spatial resolution of the investigations and evaluations involved will be collected.

(iv) Uplift/erosion assessment technology

In order to improve the reliability of the assessment of future uplift and erosion, characterisation technologies will be improved through the expansion of applicable methods over timescales ≈ 100 ky – 1 My.

More specifically, in addition to conventional topographical methods using marine/river terraces and dating of sediments (e.g. chronology using regional volcanic ash), thermochronological methods that combine mineral closure temperatures with radiometric dating, and methods combining chemical analysis and dating of locally distributed sediments, will be further developed.

For coastal areas, especially those where indicators are scarce, the following will be assessed: case studies on exposure dating based on the accumulation of cosmogenic nuclides in rock erosion terraces; correlation and chronology of terraces using empirical weathering indices for gravel layers and soils; terrain analysis using high precision digital terrain data; and extrapolation of land uplift and erosion patterns to coastal marine areas based on topographic and geological profiles. By combining these methods, determination of uplift and erosion in both coastal land and sea areas will be improved.

(v) Development of evaluation technology related to the probability and impact of long-term natural perturbation phenomena

To improve the reliability of assessments of the likelihood of occurrence and impacts of relevant phenomena for periods $> \approx 100$ ky, for which uncertainties are currently considered to be large, the established TOPAZ methodology will be expanded and improved.

More specifically, considering regional characteristics in terms of future tectonic plate movement, changes in climate and sea level and the characteristics of specific perturbations in terms of their development over time, NUMO will systematically develop scenarios of potential future perturbations over time periods up to ≈ 1 My. Even for areas selected due to low risk of such perturbations, scoping assessment of impacts occurring only in the far future (e.g. $> \approx 100$ ky) will need to be assessed. Furthermore, to assure traceability, rigorous methods will be used to capture the expert knowledge required to stochastically quantify the phenomena modelled along with associated uncertainties. This approach will be applied, in particular, to earthquake/fault activity and uplift/erosion assessment.

(2) Determination of geological characteristics and their evolution

(i) Development of technology for determining hydraulic and solute transfer characteristics of water-conducting features

Determining the regional groundwater flow field, including recharge and discharge areas, together with identification of areas where groundwater remains effectively stagnant for long times, is essential in the PI stage. To improve the investigation approach, as well as associated analysis of water and solute transport, a methodology tailored to the temporal/spatial scales of interest will be developed.

More specifically, for the regional groundwater flow field, the validity of flow analysis models will be tested by assessing consistency of results with characteristics that are constrained by such flow, such as the spatial distribution of groundwater chemistry and apparent age. Furthermore, a methodology will be developed for assessing the impacts of heterogeneity of flow/transport, e.g. due to the distribution of water-conducting features in fractured rock.

For the specific case of rocks containing fossil seawater, evaluation of paleo-hydrogeological changes, coupled to tailored approaches combining borehole and geophysical investigations, will allow us to better understand if this can be taken as evidence of long-term stability of hydrogeochemical conditions.

(ii) Development of investigation and evaluation technologies under the coastal seabed

As investigations extending from coastal land to the sea are likely to be required at the PI stage, required technology has to be developed and tested, with special emphasis on determining hydro-geochemistry and its long-term evolution.

Although technologies for three-dimensional geophysical exploration, borehole investigations, etc. have been applied to coastal sea areas as part of resource exploration or academic scientific studies, their direct applicability or ease of modification to meet the requirements of site investigations for geological disposal will be evaluated. As in the case of land areas, a focus is on the geoscientific information and quality levels necessary to assess engineering feasibility and post-closure safety. Furthermore, through case studies in which a combination of investigation technologies are implemented and their applicability assessed, the specific technology needed to characterise long-term stable hydraulic and chemical conditions - including the impacts of faults on groundwater flow – will be developed.

(iii) Advanced models of long-term evolution of geological environmental characteristics

NUMO will develop long-term evolution models (4D SDMs) that form the basis for repository design and post-closure safety assessment. This is essential during the PI stage and necessary to support arguments of the suitability of specific geological settings.

More specifically, the validity of the 4D models of hydraulic/chemical conditions will be tested through appropriate case studies that include relevant changes in geo-environmental characteristics, e.g. due to fault movement. NUMO will also utilise this approach to develop credible scenarios of future evolution of hydrogeochemical conditions. Using the SDMs already developed for the three representative host rocks, the latest scientific knowledge to better represent the impacts of processes such as deep penetration of oxidising waters, long-term topographic changes, and climate/sea-level changes will be captured. Through these efforts, incorporation of increased realism into safety assessments will be facilitated.

(iv) Development of borehole investigation/monitoring/sealing technologies

As a requirement for the PI stage, NUMO will systematically develop required borehole drilling, site investigation, long-term monitoring and sealing technology.

More specifically, drilling during the PI stage may encounter rocks in which borehole stability is an issue and hence knowledge and technology available to optimise counter-measures or responses to any problems encountered (e.g. modifying drilling mud and/or drilling technology used) will be assured. Borehole logging/investigation/testing as well as studies of water and core samples will be tailored to conditions experienced and technology used to preserve hole stability, minimise perturbations and assure that characterisation goals are reached with the required quality levels.

Monitoring technology for characteristics such as rock deformation and groundwater pressure/chemistry in boreholes will be improved using fibre-optic technology in order to widen applicability, practicality and accuracy for long-term in-situ monitoring with timescales up to several decades. Applicability of this technology will be tested in advance in existing boreholes.

There is an internationally recognised need to ensure that boreholes do not become preferential water-conducting pathways after closure of the repository. The required technology for recovering test equipment/casing pipes from boreholes as well as selecting/emplacing borehole sealing materials, will be developed and field tested for relevant geological environments, ideally within an international collaboration framework.

(3) Strengthening the technical basis for site investigations

To assure effective and reliable site investigations can be carried out, required technical infrastructure will be established, e.g. by compiling relevant scientific knowledge, building on focused R&D, and further development of a tailored quality management system.

More specifically, NUMO will prioritise expanding scientific knowledge on Pre-Neogene sediments, particularly within accretionary structures, due to the limited information base currently available. Bearing in mind that site investigations are both complex and highly sensitive, capture of direct experience in geological characterisation and evaluating long-term evolution, as discussed in Section 3.5.2 (2) above, is a priority – e.g. taking advantage of the resources developed in JAEA's URL programmes. Priority is also placed on experience in geological investigations in relevant land and coastal sea areas, including planning and application in terms of methodology, effectiveness and other technical issues. Furthermore, effective quality management and data management systems are needed, based on those already applied to site investigations and tailored to improve effectiveness based on practical experience gained by applying them to borehole investigations, as discussed in Section 3.5.2 (2) (iv) above.

Supporting Reports (SRs)

SR 3-1 Review of conclusions on the geological environment in Japan provided by the H12 Report
SR 3-2 Evaluation of the likelihood of natural perturbations (basic concepts)
SR 3-3 Evaluation of the likelihood of natural perturbations (volcanic and igneous activity)
SR 3-4 Evaluation of the likelihood of natural perturbations (earthquake and fault activity)
SR 3-5 Evaluation of the likelihood of natural perturbations (uplift and erosion)
SR 3-6 Evaluation of likelihood of natural perturbations (combinations of investigation techniques)
SR 3-7 Characterisation of geological environments (basic concepts)
SR 3-8 Characterisation of geological environments (information flow)
SR 3-9 Characterisation of geological environments (combinations of investigation techniques)
SR 3-10 Evaluation of long-term evolution of geological environments
SR 3-11 Summary of investigation techniques
SR 3-12 Quality management during site characterisation and SDM development
SR 3-13 Identification of potential host rocks
SR 3-14 SDM development for plutonic rocks (creation of dataset)
SR 3-15 SDM development for plutonic rocks (setting areas and conceptual models)
SR 3-16 SDM development for Neogene sedimentary rocks (creation of dataset)
SR 3-17 SDM development for Neogene sedimentary rocks (setting areas and conceptual models)
SR 3-18 SDM development for Pre-Neogene sedimentary rocks (creation of dataset)
SR 3-19 SDM development for Pre-Neogene sedimentary rocks (setting areas and conceptual models)
SR 3-20 SDM development for plutonic rocks (regional scale model)
SR 3-21 SDM development for Neogene sedimentary rocks (regional scale model)
SR 3-22 SDM development for Pre-Neogene sedimentary rocks (regional scale model)
SR 3-23 SDM development for plutonic rocks (repository scale model)
SR 3-24 SDM development for Neogene sedimentary rocks (repository scale model)
SR 3-25 SDM development for Pre-Neogene sedimentary rocks (repository scale model)
SR 3-26 SDM development for plutonic rocks (panel scale model)
SR 3-27 SDM development for Neogene sedimentary rocks (panel scale model)
SR 3-28 SDM development for Pre-Neogene sedimentary rocks (panel scale model)
SR 3-29 SDM development for plutonic rocks (water-conducting microstructure model)
SR 3-30 SDM development for Neogene sedimentary rocks (water-conducting microstructure model)
SR 3-31 SDM development for Pre-Neogene sedimentary rocks (water-conducting microstructure model)
SR 3-32 Modelling of groundwater chemistry of representative potential host rock settings
SR 3-33 Modelling of thermal and mechanical properties of representative potential host rock settings
SR 3-34 Likelihood and potential impacts of future natural perturbations (magma intrusion and eruption)

SR 3-35 Likelihood and potential impacts of future natural perturbations (earthquake and fault activity)

SR 3-36 Likelihood and potential impacts of future natural perturbations (uplift and erosion)

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4 REPOSITORY DESIGN AND ENGINEERING TECHNOLOGY

Based on the basic concept of repository design described in Section 2.3, this chapter will present the following:

- Repository design specifications to demonstrate the engineering practicality of construction, operation and closure of facilities tailored to the three representative host-rock site descriptive models (SDMs) presented in Chapter 3, which will provide the basis for assessing safety, both pre and post-closure.
- Illustration of a practical design methodology that can respond to the geological environments expected to be encountered at volunteer sites, such as the presence of faults, and determine pros and cons of different disposal concepts.
- Analysis of such designs (see Section 4.2.4 (ii)) to show that they have the potential to provide the required safety functions for specific SDMs and that they can be implemented using engineering technology available at present, or that which will be realised in the near future. However, the impact on the safety functions if conditions change, e.g. due to natural perturbations, can only be assessed as part of the scenario analysis presented in Chapter 6.

In Section 4.1, the development of repository concepts using a structured methodology is described, based on design factors to ensure flexibility for the variety of geological environments and social boundary conditions. Section 4.2 explains the basic design procedure for the repository, based on the characteristics of the waste and the SDMs, together with required pre- and post-closure safety functions. In Section 4.3, the repository disposal depth is set while, in Section 4.4, the design of the engineered barriers is described. This leads to specification and illustration of underground facilities in Section 4.5, and surface facilities in Section 4.6, which provide the required safety functions. Technology related to construction, operation and closure of these facilities is also discussed as a basis for subsequent safety assessment. Section 4.7 assesses the engineering practicality of waste retrieval during the period until acceptance of the safety case is confirmed, prior to closure of the repository. Finally, Section 4.8 summarises the chapter and outlines future activities in this field.

4.1 Approach to development of repository concepts

The purpose of repository design is to develop specifications of the facilities required to ensure safe waste disposal during operation of the repository and ensure passive safety thereafter without any active institutional control. With this aim, design technology development is based on the following thinking [1]:

- In order to be able to focus design to both assure safety and also engineering practicality during the process of stepwise site selection, the multifaceted repository requirements are captured as “design factors”.
- Disposal concepts and design options are developed in such a way that it is possible to respond flexibly to the diverse geological environments that may result from the siting process, together with progress in science and technology during the long project implementation period (in the order of a century).
- In accordance with the stepwise narrowing of the scope of investigation and the refinement of the geological knowledge base, the repository will be designed using SDM information and data appropriate to the spatial scale involved.

In this section, a design methodology developed on the basis of these ideas is described.

Repository design will be optimised in steps; starting from a conceptual design, followed by a basic design and finally a detailed design that will be tailored to developing understanding of the site geological environment.

The conceptual design is a first repository outline based on the SDM resulting from surface exploration or boreholes included in the preliminary investigations (PI), but design work actually starts during the literature survey (LS) phase. Based on the conceptual design, safety assessment will be carried out to confirm the practicality of geological disposal, e.g. based on the mechanical and hydraulic properties at relevant depths underground. The design options developed will be narrowed down for the demonstration of engineering practicality in the next step.

An underground investigation facility (UIF) will be constructed in the target host rock(s) during the DI phase to confirm important properties, such as mechanical, hydraulic, thermal and chemical suitability. In addition, construction and operational technologies will be demonstrated in the UIF (although, due to time constraints, initial development work will be carried out in existing URLs). The basic design will be tailored to the updated SDM, with illustration of feasible engineering of repository construction and operation. The safety case will be developed for this basic design and applied to the licence application.

After passing the licence application, the basic design will be used as a starting point, allowing detailed design of the equipment related to construction and operation to be carried out, with final design of the repository beginning after construction approval. In this way, throughout the site selection process, the repository is designed in an iterative manner, with optimisation on the basis of continual assessment of safety and practicality.

In the H12 report, examples of 2 conceptual disposal designs for HLW (in-hole vertical and in-tunnel horizontal (H12V/H12H) applicable to a wide range of geological settings in Japan were presented, with limited consideration of site environmental characteristics. As further discussed in Section 4.2.3, the selection of the design concept should originate from the defined requirements. However, for the current version of the safety case, focus is on already relatively well-assessed concepts, such as presented in the H12 report for HLW and the TRU-2 report for TRU waste, in order to show how requirements are used to further specify the design. Considering that the current stage is prior to starting the LS, the three representative SDMs developed in Chapter 3 were used. The repository was designed with the objective of showing how it can be adapted to site conditions. Therefore, the amount of waste handled and the operational methods are set provisionally, with equipment used for construction and operation illustrative only. In the future, more detailed design work will be conducted in parallel, to confirm fundamental practicality through demonstration tests.

4.1.1 Capturing requirements in design factors

Based on nuclear safety regulations, since 2005, repository designs are required to be in accordance with a performance code instead of the specification code previously used (see “Ministry Ordinance No. 62: order that establishes technical standards for power generation nuclear facilities”). The performance code obliges NUMO to utilise best available technology (BAT) during the development of the repository over the next few decades. It is worth noting that such flexibility of design methodology might facilitate tailoring the repository design to the site.

“Design factors” provide a consistent focus for repository design that is applicable to different sites and different stages of project development [2]. The following issues are considered when setting the design factors:

- Those concerning the safety of the repository, as indicated by the regulations of international organisations for related nuclear facilities.
- Relevant Japanese policy, such as the Basic Policy on Final Disposal of Designated Radioactive Wastes (Basic Policy on Final Disposal – see Chapter 1).
- Issues pertaining to the practicality and economics of the design, construction and operation of repositories.

In this chapter, it was decided to consider five groups of requirements that constrain design factors: operational safety, long-term safety after closure, retrievability, engineering practicality and socio-economic issues[1]. The resulting design factors to meet these requirements are shown in Table 4.1-1.

Table 4.1-1 Design factors and related requirements considered in this report

Design factor	Specific requirements
Operational safety	• Prevention of leakage of radionuclides (RNs) from waste • Prevention of release of RNs from the repository • Radiation shielding • Prevention of occurrence and propagation of incidents • Evacuation routes established in case of accidents • Maintain conditions appropriate to worker health and safety
Post-closure safety	• Protection from significant effects of natural perturbing phenomena • Reduction of the likelihood of human intrusion • Restriction of RN leaching • Restrict of RN migration
Retrievability	• Maintain practicality of retrieval of waste • Avoid any reduction of safety margins as a result of maintaining ease of retrieval
Engineering practicality	• Fundamental practicality of construction, operation and closure of all facilities • Application of proven technology
Socio-economic issues	• Cost-effectiveness of construction, operation and closure of repository • Assured ability to procure all support materials/services required

Among the design factors, requirements in terms of operational safety functions are defined in relevant laws and regulations applicable to industrial and nuclear facilities, as summarised in Tables 2.1-3 and 2.1-4 in terms of radiation protection and general occupational safety, respectively. Post-closure safety requirements for geological disposal are derived from IAEA [3] and a report on safety regulations [4], which are summarised in Table 2.1-5 in terms of containment and isolation safety functions. Further, Section 2.1.3 (2) discusses assuring practicality of waste retrieval in order to provide options for future generations to reconsider

[1] Additional factors such as environmental conservation are not currently considered in this report, as these require more specific information about the geographical, geological and social conditions of the site. Environmental monitoring of the impacts of repository implementation is, however, considered in Chapter 2 and will form the basis of developing environmental design factors to be used in the future.

this choice of disposal method and hence "retrievability" was set as a design factor in NUMO (2004) [2]. Finally, "engineering practicality" and "socio-economic issues" are set in order to assure that designs developed can actually be implemented based on real world constraints, reflecting NUMO's role as an implementer and the need to develop and manage a viable project. Hence this is a significant development from the previous studies undertaken by R&D organisations in Japan.

4.1.2 Setting and utilising design requirements

As shown in Figure 4.1-1, design factors are key to assuring the required performance of the repository, defining requirements for each component to allow specifications to be derived.

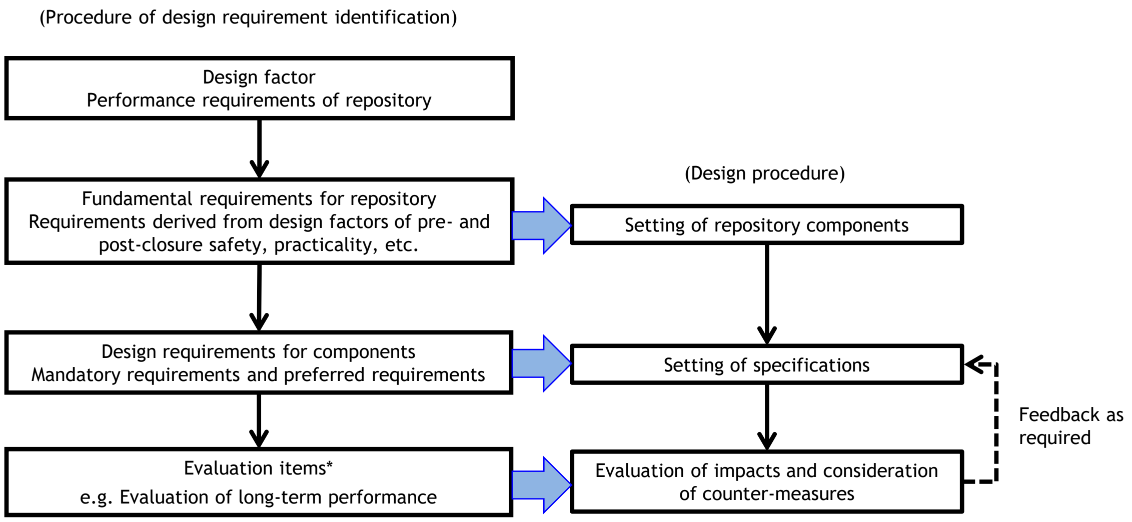


Figure 4.1-1 Role of design factors in the design process

Design requirements can be categorised as those that must be fulfilled to ensure the required performance (mandatory requirements) and those to further improve the performance (preferred requirements). Design is then performed using these requirements, and basic specifications (materials, shapes, dimensions, etc.) are set.

For specifications designed to satisfy these requirements, evaluation items are selected by identifying the influence factors that can lead to loss of function and/or decrease in long-term performance before or after repository closure. The influence factors can be classified in to thermal, hydrogeological, mechanical and chemical impacts over the long-term (which may be effectively permanent), as assessed and described in this chapter. Chemical behaviour which may directly impact RN migration in the near-field is assessed in Chapter 6 (see Table 6.3-1). If these impacts are significant, either, counter-measures will be implemented, or specifications for the repository component will be iteratively optimised to mitigate the impact.

For quality assurance of design work, it is necessary to ensure the models and analysis codes used are adequately tested, meet their defined specifications and conform to requirements to manage information properly. The codes used in this work are listed in Supporting Report 4-1.

4.1.3 Development of design options

It is not necessary to narrow down to a single reference design at present, especially considering the diverse geological environments found in Japan. Rather, in this stage without a specific site, maintaining a range of designs that meet the requirements of the design factors allows flexibility to tailor design to site characteristics.

Even if technology is considered to have poorly-demonstrated engineering practicality at present, consideration of an extensive range of design options allows identification of appropriate technology that can be developed further in the future. As a result, it is considered possible to adapt designs to reflect progress in science and technology and improve resultant performance. This idea, focusing on BAT, is consistent with international guidance on safe implementation of geological disposal [5].

Based on this approach, NUMO and related research institutes have been developing a number of design options. Specifically, H12 [6] provides a starting point for design specification of the engineered barriers for HLW, together with the layout of the emplacement and other underground facilities. This base has been expanded further by NUMO and organised as a “repository concept catalogue” [7]. Several novel design options presented in this catalogue, following subsequent technical development, have been shown to be based on practical and promising technology. Based on progress in development of these design options, repository concepts that form the basis of designs described in this report are selected (see Section 4.2.3).

Figure 4.1-2 classifies, in general terms, many of the repository concepts examined in Japan and abroad since H12. For example, most effort has been on options to place the waste in tunnels, vaults or holes accessed by shafts and/or ramps.

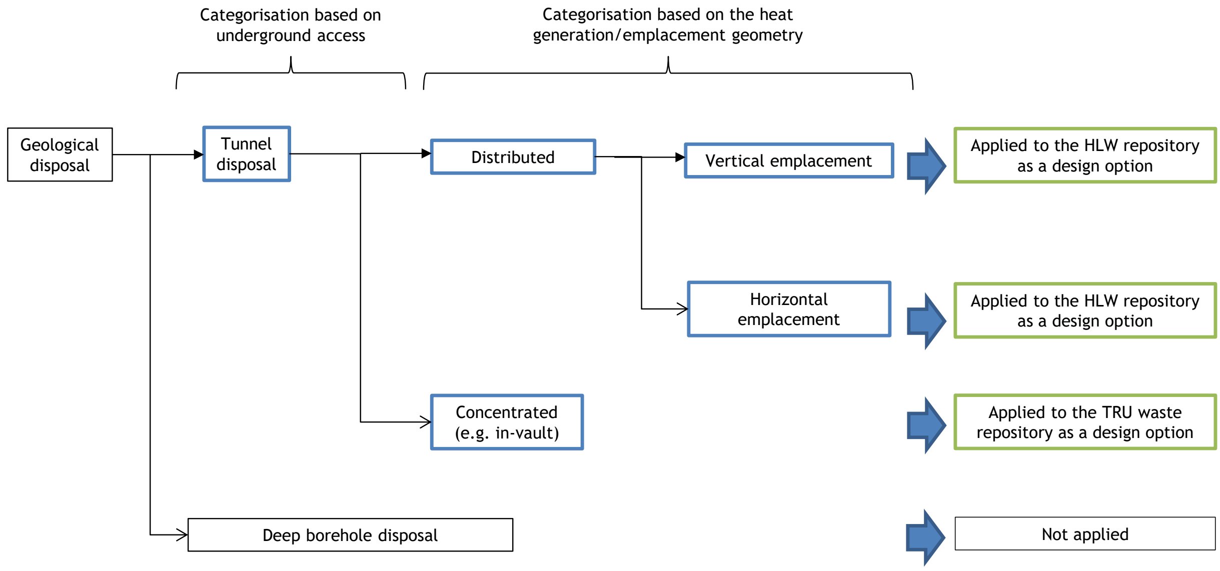


Figure 4.1-2 Classification of repository concepts

Overseas deep borehole disposal[2] has been discussed but, amongst other things, it is particularly unclear whether this concept would be practical for Japan's large waste inventory. Tunnel-type disposal can be further classified as either distributed or concentrated, depending on the density of waste emplacement. In order to reduce the temperature rise in the host rock, a distributed concept is generally applied to waste with high thermal output – such as HLW. In this study two variants of this are considered, horizontal in-tunnel emplacement and vertical emplacement in holes in the tunnel floor. It is clearly recognised that these concepts can be further optimised and that alternate concepts might be applicable in Japan.

To increase efficiency of operations and use of underground space, concentrated disposal concepts are generally applied to waste with lower heat output, such as TRU waste, as discussed further in the TRU-2 report [10] and adopted for our studies in this chapter.

[2] Deep borehole disposal (DBD) involves waste emplacement in the lower parts of holes drilled from the surface [8]. Like other forms of geological disposal, safety is provided in terms of forming multiple barrier systems with engineered barriers and natural rock. Most countries planning geological disposal, including Japan, have considered tunnel-type disposal. However, in recent years, DBD has been studied as an alternative concept, mainly in the United States. While this disposal method can minimise underground excavation, it is considered that there are problems such as restriction of the borehole size and difficulty of recovery [9].

4.2 Repository design procedures and boundary conditions

4.2.1 Repository design procedures

The repository design work flow based on requirements was introduced in Section 4.1.2 and is shown in Figure 4.2-1. This requires specification of the characteristics of waste assigned to geological disposal, as presented in Chapter 2, and the details of the representative SDMs, presented in Chapter 3.

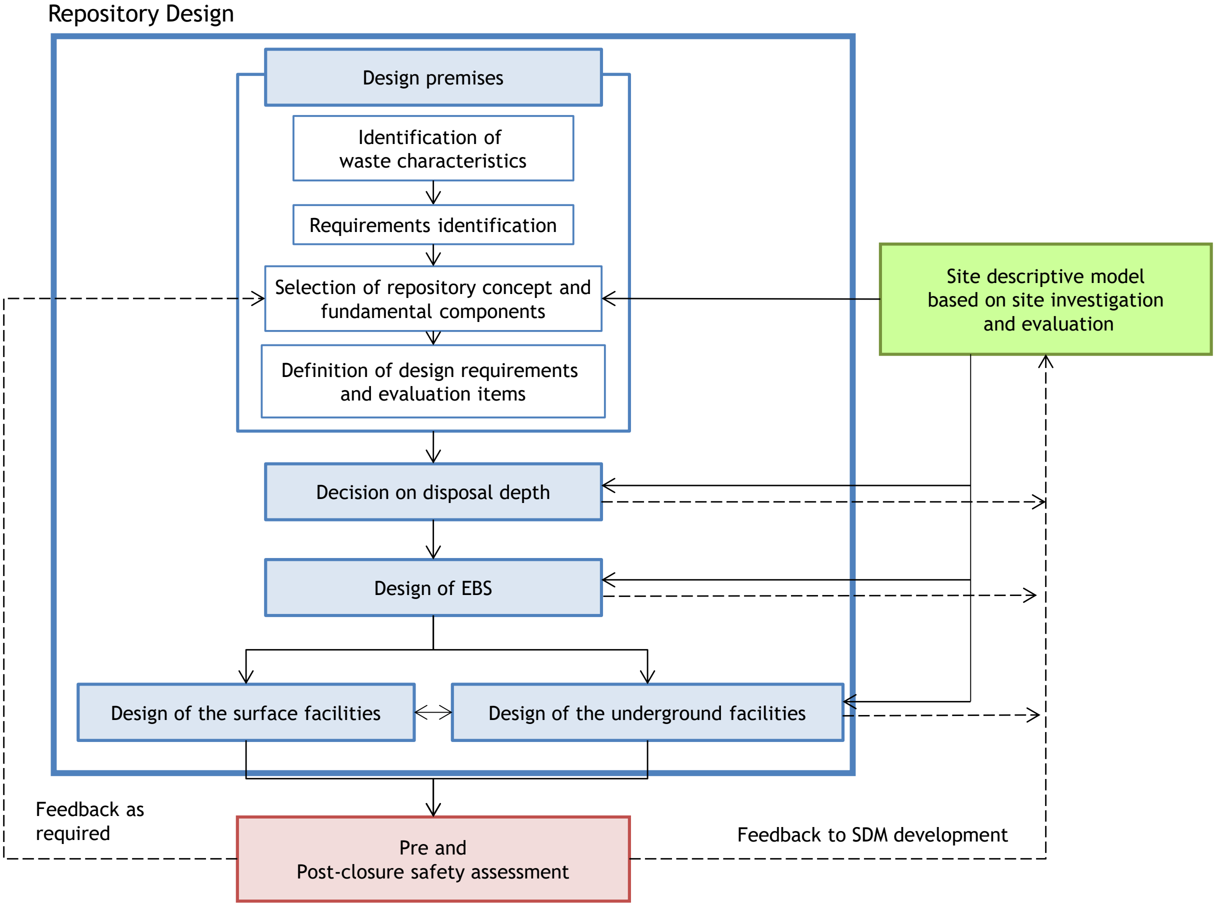


Figure 4.2-1 Repository design work flow considering technical feedback loops. Some aspects (such as the potential revision of requirements due to interests of stakeholders) are not directly indicated

Based on the requirements indicated in Table 4.1-1, the components of appropriate disposal concepts and associated facilities (engineered barriers, surface facilities, underground facilities) can be developed. In particular, the requirements in Table 4.1-1 for pre- and post-closure safety (see also Section 2.1.2) are allocated to specific components on the basis of similar facility designs in Japan and overseas. From this background, the disposal depth is set with reference to specific SDMs, based on design requirements.

In the design process, it is normal practice to allow for a margin of safety to take into account the uncertainties in the geological characteristics presented in the SDMs. In addition, there may be other uncertainties to consider, such as those associated with the coupled thermal, hydraulic, mechanical, chemical (THMC) processes in the buffer. However, safety margins need to be set rationally to ensure practicality and prevent complications caused by over-design, so this uncertainty should be reduced in the design process, providing feedback to improve the focus of geological characterisation. Further, if subsequent pre- or post-closure safety assessment of the preliminary repository design indicates requirements cannot be met or safety margins demonstrated, such feedback helps focus design improvement.

At this time, as sites are not yet specified, it is possible only to provide guidance for representative potential siting environments. Nevertheless, this exercise will demonstrate our capability to construct appropriate repository concepts for these. The associated guidance for rational repository design involves:

- Incorporating a common set of fundamental engineered barriers that are applicable to a range of geological environments, to which detailed specifications can be tailored on a site-specific basis.
- Underground facilities are specified for the geological structures and physical properties of the rock set on the basis of the SDMs.
- Surface facilities, including waste reception, inspection and encapsulation plants, are designed with an emphasis on work flow and radiation protection during the operational period, which have a low sensitivity to the site geological environment.

In the following, boundary conditions for design, waste and geological characteristics that set requirements for specific repository components are presented.

4.2.2 Waste characteristics

Specified waste for deep geological disposal includes HLW and TRU waste. This section presents quantities of such waste and other characteristics relevant to design, such as heat output and radioactivity.

(1) HLW

As mentioned in Section 2.1.1 (1), although HLW produced by different manufacturers has different specifications, for the design of the repository, the specifications for HLW produced by JNFL is taken as a reference. The final disposal plan specifies a requirement to dispose of at least 40,000 HLW canisters (see Section 2.1.1 (4)), with this minimum value taken as the reference for design purposes.

High-level radioactive liquid waste is calcined, vitrified with a borosilicate glass frit and poured into a cylindrical stainless-steel canister, with an outer diameter of 0.43 m and a height of 1.34 m. Assessments of the radioactivity inventory and heat output of HLW are given in Supporting Report 2-2. Heat output of a HLW canister, in the case of a four-year spent fuel (SF) cooling period before reprocessing and a period of 30 or 50 years storage before disposal, is about 560 W or 350 W respectively, with total radioactivity being about 4×10^{15} Bq and 2×10^{15} Bq at these times. About 1 ky after disposal, the total radioactivity is around 10^{13} Bq/HLW canister.

As mentioned in Section 2.1.1 (1), interim storage time after HLW production is not yet specified but is expected to lie in the range of between 30 and 50 years. Therefore, in this report, in order to highlight and quantify differences in potential representative host rocks, designs were developed for storage periods of both 50 and 30 years (with the latter being hotter and more radioactive). This will, however, be reassessed in the future when the inventory in general, and this parameter in particular, is better defined.

To assess operational safety functions (see Section 4.2.4 (1)), including those above and below ground during waste handling, encapsulation, transport and emplacement, shielding and dose calculations are conservatively based on the radioactivity inventory of HLW stored for 30 years.

Post-closure safety functions (see Section 4.2.4 (2)) are important in the design of engineered barriers, such as overpack or buffer material specifications and the underground layout of the disposal tunnels. For this purpose, it is necessary to set the radioactive inventory of the HLW and its associated thermal characteristics. Generally speaking, for shorter pre-emplacement storage, the footprint of the repository and excavation volume become larger, also increasing repository-driven perturbations – e.g. of hydrogeological conditions. To ensure safety after closure, preferred characteristics of the geological environment (Section 3.1.3 (2)) should be disturbed as little as possible, thus the inventory of HLW with a storage period of 50 years was considered as the design base. Nevertheless, it is technically possible to design underground facilities for HLW with a storage period of 30 years, e.g. by increasing temperature limits on materials, decreasing the disposal depth, etc. In the future, technology to allow design optimisation considering the variability of the inventory due to differences in interim storage time will be developed.

(2) TRU waste

TRU waste is inherently very heterogeneous, with the defined groups containing different waste streams from different producers, a significant quantity of which will arise only in the future. For safety assessment in this report, representative package specifications are defined for each group. In the future, however, the ranges of waste properties will be considered in more detail.

TRU waste form (drum, canister, box, etc.), size, and weight, were described in Section 2.1.1 (2) based on the TRU-2 report [10] and NUMO (2011) [11]. As for HLW, the interim storage time between waste production and disposal is not defined for TRU waste. The TRU-2 design and recent safety assessment reports [11] [12] used a thermal and radioactivity inventory at 25 years after production, which is also assumed here.

In the TRU-2 report, Group (Gr.) 1 waste is assumed to be grouted into 200 l drums. This waste contains a large inventory of radioiodine (I-129), which can dominate impacts due to its generally low sorption and high solubility, and led to work at relevant research institutes to reduce its leach rate by development of alternative solidification technology options. As a result, various alternative conditioning processes have been shown to have the potential to reduce the leaching rate over a period of about 100 ky [13]. However, full-scale production technology and assured performance under relevant geological conditions have yet to be demonstrated for these approaches. Thus, this report conservatively assumes cement conditioning of Gr.1 waste.

In addition, also for waste Grs.2, 3, 4L and 4H, heat output, radioactivity, volume, weight, etc. were set to be conservative for design purposes (data summarised in Supporting Report 2-4).

4.2.3 Disposal concepts and components

Basically, the selection of the design concept should originate from the defined requirements. However, for the current version of the safety case, focus has been on already relatively well-assessed concepts, such as presented in the H12 report for HLW and the TRU-2 report for TRU waste, in order to show how requirements are used to further specify the design. A more open and general approach, also considering other potential concepts, will be applied in the future, especially if it turns out that the geological environments at potential sites significantly deviate from the SDMs considered in this report. It is also recognised that more optimal concepts might be derived, even within the range of siting environments studied in this assessment.

(1) Setting of the basic disposal concept

Of the general geological disposal options indicated in Figure 4.1-2, requirements such as proven technology, ease of quality control, retrievability, etc. lead to selection of a mined repository concept, as illustrated in the H12 report. For heat-emitting HLW, distributed disposal is selected, with options of vertical or horizontal emplacement considered. Lower heat TRU waste can be more efficiently emplaced using a concentrated emplacement concept.

As mentioned in Section 2.1.1 (5), in this report co-location of disposal facilities for HLW and TRU waste is assumed. Such co-disposal has clear benefits in terms of efficiency of implementation due to sharing site survey results and some surface facilities, provided the available site would allow the resulting footprint. However, it is necessary to keep any interactions between the two disposal facilities as small as possible [10] [11]. In the following, the engineered barriers, underground and surface facilities are discussed based on the disposal concepts set out above.

(2) Engineered Barrier System (EBS)

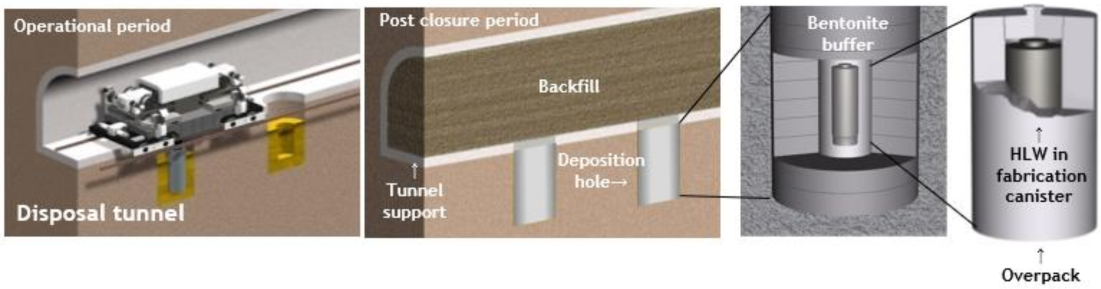
(i) EBS for HLW

The EBS variants considered in this report are all taken from existing designs and illustrated in Figure 4.2-2. Their derivation from requirements is discussed in following sections of this chapter. The EBS comprises multiple barriers, including the borosilicate glass matrix (and the fabrication canister within which it is contained, although this is conservatively ignored), the overpack and the buffer.

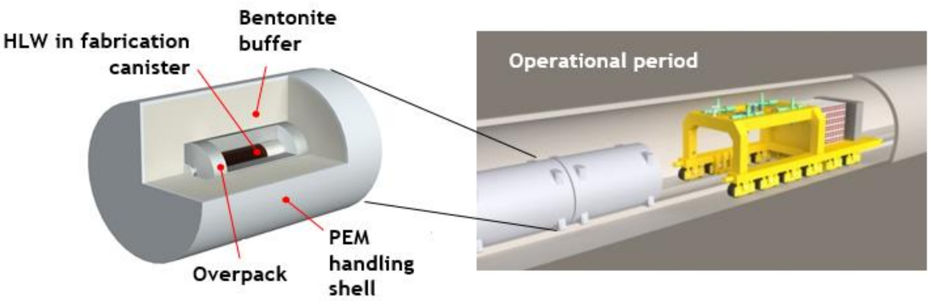
The overpack may be made from carbon steel, copper or titanium. Metal overpacks are considered in this assessment because they are commonly used in many industries and much experience in container manufacturing exists. In addition, metal overpacks are also chosen as the reference material for waste containers by almost all international implementers of geological disposal of HLW or SF.

Bentonite, which contains high concentrations of swelling clay minerals (e.g. smectite), has the capacity to provide physical and chemical buffering in the repository [6] and is a promising buffer material. Alternative materials, such as mortar or resin, could be also considered, but they may require additional assessment to ensure all of the expected roles for the buffer are provided. Bentonite is therefore chosen by most repository implementers.

For vertical in-hole emplacement (H12V), the option of in-situ buffer construction using compacted bentonite blocks is selected on the basis of wide international experience [14] although other options have been studied in Japan [15]. For horizontal in-tunnel emplacement, a PEM (Prefabricated Engineered barrier system Module) option is selected to ensure ease of emplacement of the bentonite buffer with the required quality by remote handling (even under wet conditions).



(a) H12V method



(b) PEM method

Figure 4.2-2 HLW engineered barriers

The PEM is similar in principle to the KBS-3H concept [16], which Sweden and Finland are examining. This allows buffer construction within the handling shell on the surface, which is advantageous in that quality control is easier and problems such as swelling of the bentonite underground due to dripping water or high humidity can be avoided. Furthermore, as described in Section 4.4.3 (1) (ii), PEMs have been fabricated at full scale and transport/emplacement tests have been carried out.

The focus in this report is thus H12V using bentonite blocks and the PEM, but other buffer emplacement options exist, for example, methods utilising horizontal pellet injection or in-situ compaction [1] [17], together with other waste package emplacement approaches.

(ii) EBS for TRU waste

The EBS for TRU waste is illustrated in Figure 4.2-3. As for HLW, the EBS comprises multiple barriers including: the TRU waste matrix and primary container (waste form), waste package and infill, concrete structures and, in some cases, a bentonite buffer. However, since the characteristics of the waste groups are different, the EBS is tailored to each of these. The waste package manufactured for disposal encapsulates primary containers holding the waste (waste form), which are surrounded by infill, as also shown in Figure 4.2-3: this is the unit considered for design of disposal vaults.

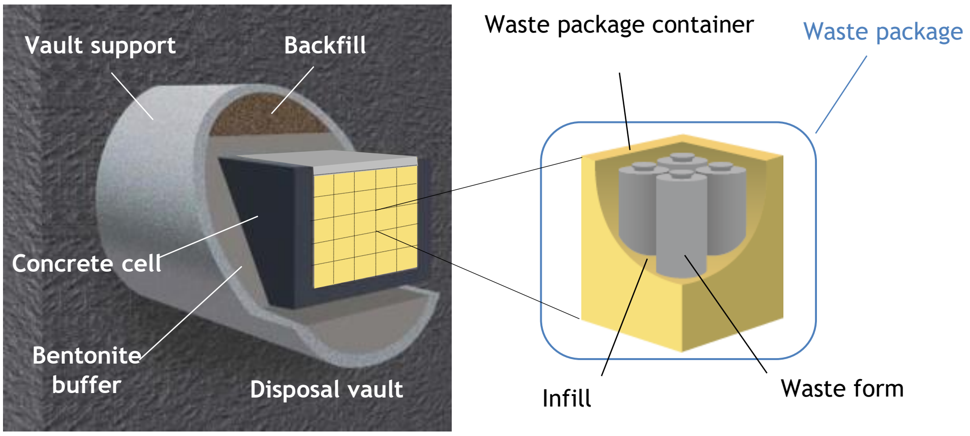


Figure 4.2-3 TRU waste engineered barriers

In the TRU-2 report, a waste package (containing the waste form) fabricated from steel with a mortar infill (termed waste package A) was illustrated; this was specifically designed to facilitate stacking with a forklift in the disposal vault. In the same report, the concept of emplacement using gantry cranes was also illustrated as a design option, but a problem identified was to reduce the risk of waste package drops during handling. However, emplacement by cranes is commonly used in low-level radioactive waste repositories in Japan [18] and overseas [19].

Since the TRU-2 report, the use of high strength/high density concrete, potential use of a titanium container for C-14 containing waste [20] and waste packages fitted with a lid (termed waste package B) were amongst the variant design options considered [11] [20]. Thus, the development of container technology is progressing, with standard [21] rectangular steel containers established for low-level radioactive waste disposal. In this report, the TRU-2 waste package A (emplaced with a forklift) and in addition, a more robust waste package B (emplaced by a crane) are both considered as options.

(3) Components of underground facilities

Figure 4.2-4 illustrates key components of underground facilities, including access ramps and shafts, disposal tunnels for HLW and vaults for TRU and associated underground connecting tunnels.

Repository closure structures (e.g. mechanical plugs and hydraulic plugs) are also shown. For TRU waste in particular, extensive infrastructure is required in the disposal vaults for transporting/emplacing waste packages and subsequent infilling/backfilling. Transport and emplacement equipment is also required for HLW (H12V or PEM), together with services for the entire repository, including ventilation, drainage, lighting, communication, etc. All such components have to be included in site-specific designs.

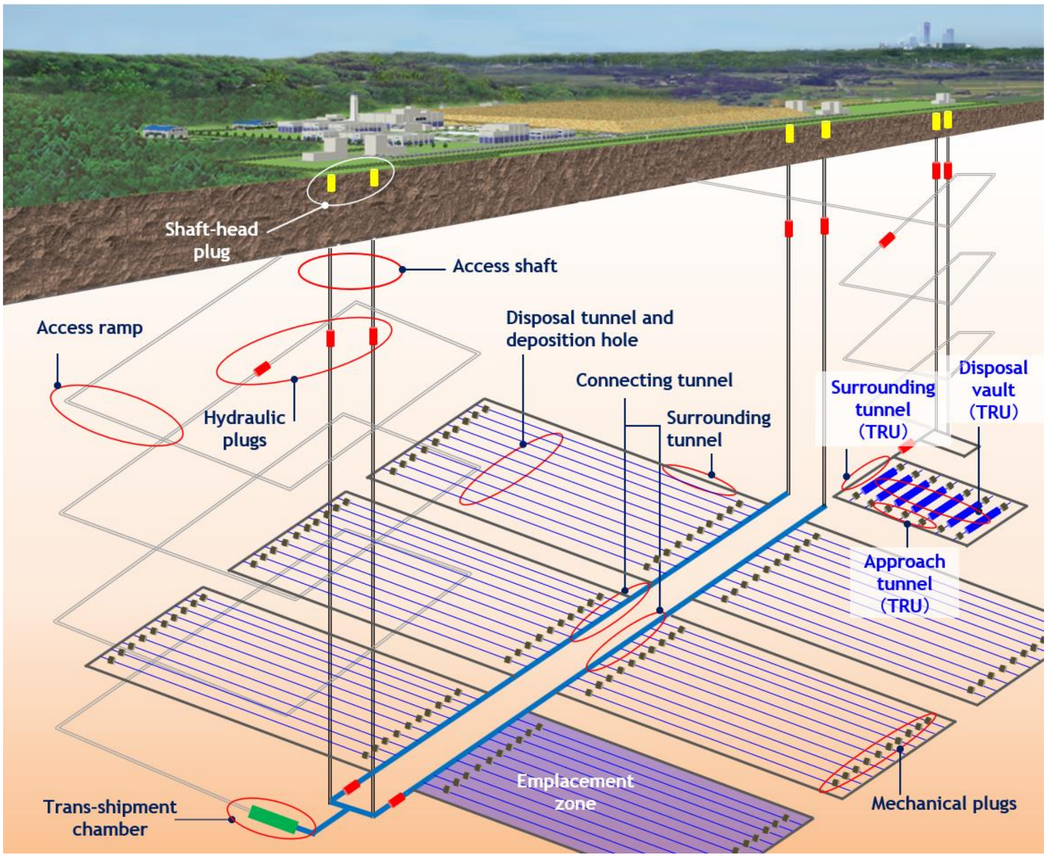


Figure 4.2-4 Sketch of key underground facilities. Note that the number of shafts and access ramps is only illustrative. In the future, efforts will be made to minimise the number of access points

(4) Components of surface facilities

The surface facilities provide the general services required for the practical implementation of this major industrial project, nuclear standard buildings for waste handling and encapsulation operations and the technical services required to support underground operations. For the case of co-located HLW and TRU waste disposal, such facilities are illustrated schematically in Figure 4.2-5.

The surface facilities consist of buildings to receive waste transported from off-site, inspect and encapsulate the HLW into the overpack and receive, inspect, encapsulate, and package the TRU waste. Also included are plants to provide ventilation, drainage and water treatment required for the construction, operation and closure of the underground facilities; a power substation (including backup power supply); an excavated spoil storage yard; and a buffer manufacturing facility. The configuration of facilities will depend on the site, potentially including port facilities and dedicated roads for receiving waste at a coastal site.

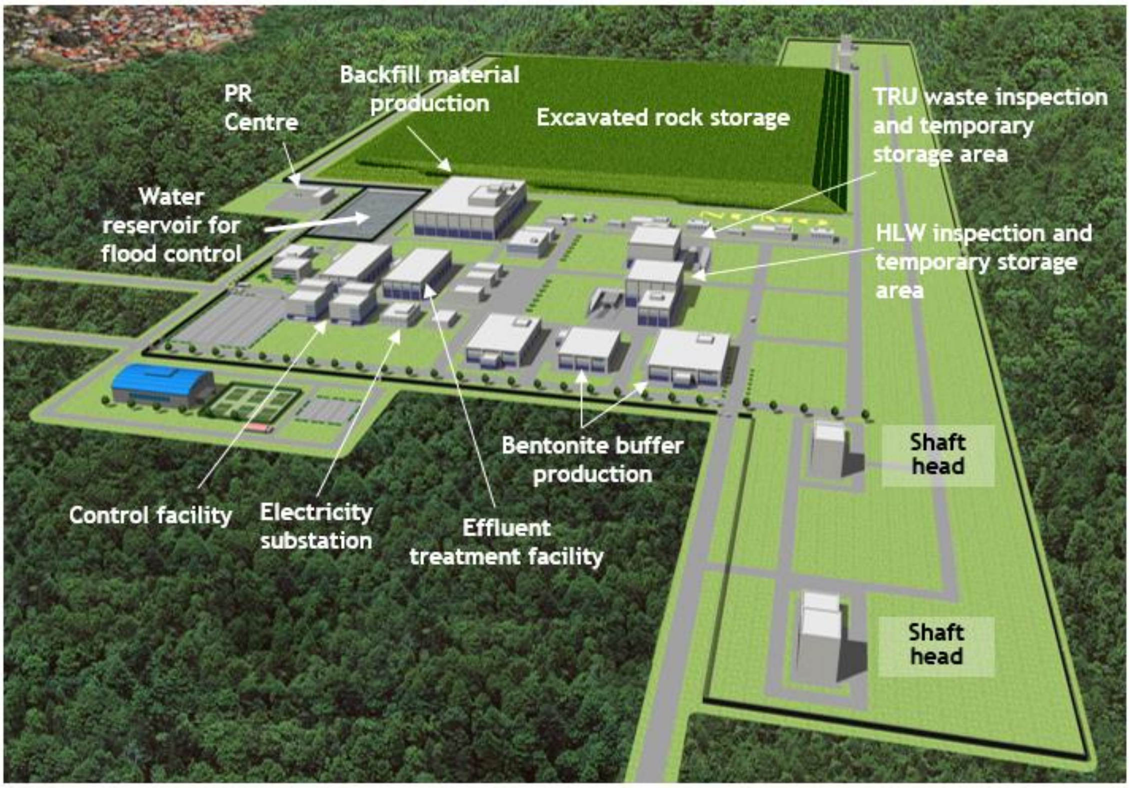


Figure 4.2-5 Sketch of key surface facilities

4.2.4 Relationship between safety functions and repository components

The repository design sets the design factors for post-closure and operational safety as a top priority (See Section 4.1.1). These requirements are referred to as safety functions (Section 2.1.2). Their relationship to the basic structure of a repository is outlined below.

(1) Relationship of operational safety functions and repository components

Operational safety considers risks to both staff and the general public during construction, operation and final closure processes. Here, after outlining operational processes, the components that are responsible for the safety functions of radiation protection and general occupational safety will be assessed.

(i) Operational processes

Repository operation can be roughly classified into the processes on the surface and those underground. These are further broken down into seven main sequential steps for operation for the H12V concept, as schematically shown in Figure 4.2-6 and discussed below.

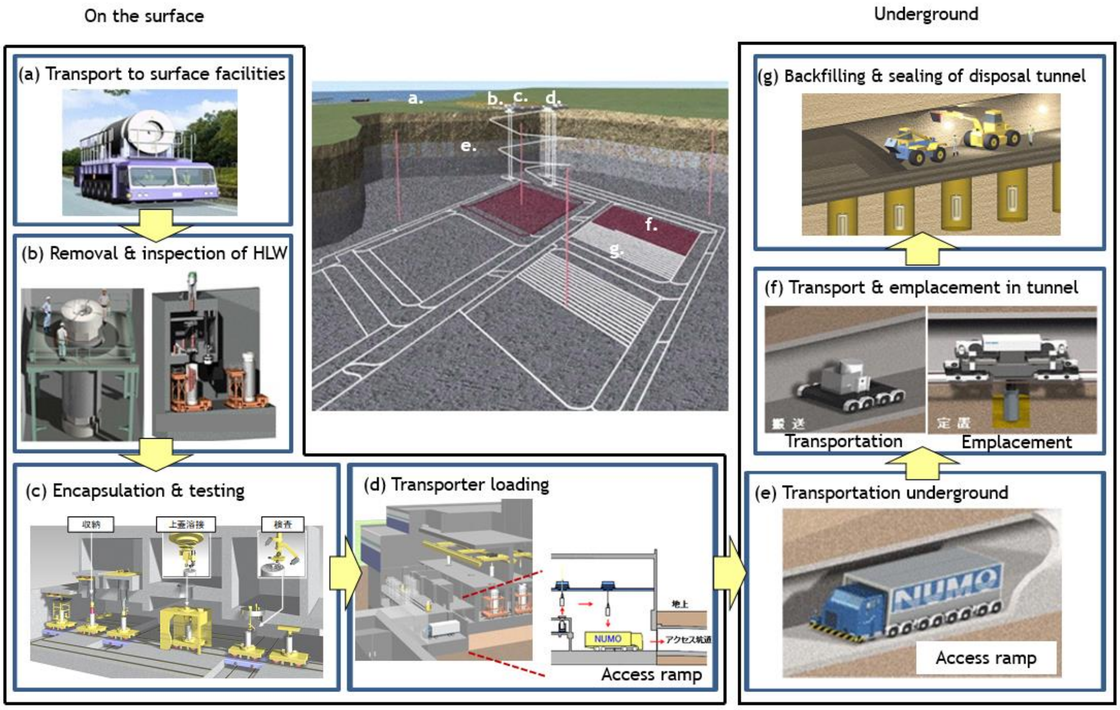


Figure 4.2-6 Repository operational steps (H12V case)

In the PEM case, an additional process of "assembling the PEM" is added between the processes of "encapsulation and testing" and "transporter loading", with the PEM loaded onto the transport vehicle instead of the overpack. For TRU waste disposal, the waste package and emplacement operations are different, but the seven steps are fundamentally the same, as also described below.

(a) Transportation to surface facilities

After interim storage for 30 to 50 years, HLW is inspected to check that characteristics meet specifications (e.g. in terms of heat output, radioactivity, waste canister characteristics) and then placed in a dedicated transportation container (cask) for transport to the repository. If it is transported by sea in a specially designed ship, the transport cask will be off-loaded at a dedicated port near the repository site and, after surface dose measurement and inspection of appearance, taken to the surface facilities on a special transport vehicle travelling on a private road. A similar process applies to TRU waste after 25 years interim storage.

(b) Reception, inspection and buffer storage

HLW/TRU waste is received at the surface facility in transport casks and placed in a temporary store which may act as a buffer store from a logistical viewpoint. After confirmation of identity and specifications, the transport cask is moved into a radiation-controlled zone and unloaded by overhead crane. Waste canisters/containers are inspected to check for abnormalities, such as damage to the waste during transport. Accepted waste is then placed in a buffer store. All operations – lifting by cranes and movement on rail transporters – are tele-operated or automated, designed to assure the required throughput while avoiding presence of staff in these controlled areas. Procedures for waste that does not meet the acceptance criteria have not yet been developed, but will be addressed in future R&D.

(c) Encapsulation of HLW in overpack/packaging of TRU waste

HLW canisters taken from the buffer store are placed into overpacks while TRU waste containers are grouted into emplacement packages. After lid sealing (currently planned to be done by welding), the overpacks/packages are subjected to non-destructive testing (e.g. using ultrasonic methods) and, after acceptance, placed in buffer stores. In the case of the PEM concept, HLW overpacks are placed into steel handling shells that are filled with buffer, sealed, tested and placed in another buffer store. Again, all processes are tele-operated or automated and plans for any overpacks/waste packages that do not pass testing have not yet been developed. However, procedures for this eventuality will be addressed in future R&D.

(d) Loading onto the underground transport vehicle

Overpacks/PEMs/TRU waste packages are taken from the buffer store and, after a check of surface contamination, moved out of the main surface facility to a transport vehicle in the access portal to the disposal facility radiation-controlled zone

(e) Transportation underground

The overpack/PEM/waste package is transported underground via the access ramp by a specially designed vehicle. At the bottom of the ramp, HLW is either placed in a buffer store or directly transferred to an emplacement machine for transport to the disposal tunnel, while TRU waste is taken directly to the waste group specific disposal vault on the transporter.

(f) Waste emplacement

HLW overpacks/PEMs are moved through connecting tunnels to the disposal tunnel for vertical/horizontal emplacement, respectively, by specially designed machines that are tele-operated or automated. For H12V, emplacement of the overpack in the disposal hole is coordinated with placing the blocks of compacted buffer around it, while the PEM is simply placed on a plinth on the disposal tunnel floor.

In the case of TRU waste, at the entrance to the disposal vault, packages are removed from the transport vehicle with either a forklift (in the case of the waste package A) or gantry crane (in the case of the waste package B) and moved to a pre-determined position inside using remote-handling technology.

(g) Backfilling and sealing

After waste emplacement, tunnels/vaults are backfilled and mechanical plugs emplaced to seal them. The operations involved depend on the waste type and disposal option, as outlined in the operational description, although details will depend on assessments of quality requirements and practicality that are ongoing at present.

(ii) Safety functions and components

Operational safety functions should take into account both expected repository operating conditions (termed the normal state) and possible deviations from these (termed abnormal states). In the normal state, the main components that contribute to radiation protection are shown in Table 4.2-1, subdivided into those that provide RN containment and those contributing to radiation shielding.

Table 4.2-1 Relationship of the operational safety functions and repository components (radiation protection) (modified from NUMO, 2011 [1])

Basic concept	Safety function	Component
Containment during operation	Prevention of leakage of RNs from waste	HLW matrix, fabrication canister, overpack, (PEM) TRU Waste matrix, container (drum, canister), TRU waste package, transport cask
	Prevention of release of RNs from the repository	Nuclear-standard surface facilities operating below atmospheric pressure, ventilation system (including exhaust filters), controlled drainage
Radiation shielding	Reduction of radiation dose	Waste package self-shielding
		Shielding walls, layout of surface facilities, locating activities below surface, access control, remote handling
		Transport shielding and shielding provided by transport vehicles

Containment of RNs during operation is assured by the waste matrix, the primary container (canister, drum, etc.), the HLW overpack and the TRU waste package, together with any additional packaging provided for transport to or within the repository. After the PEM is fabricated, the buffer and the handling shell provide further containment for HLW. After receipt, all waste handling operations take place in zones designated as the radiation control areas and, particularly those where there is a risk of contamination, operating under negative pressure prevents the release of airborne contamination. Nuclear standard construction and surface decontamination processes, ventilation and drainage prevent RNs from being released from the facility in solid, liquid or gaseous form.

With regard to radiation shielding, a basic measure is to properly design the thickness of the shielding walls of relevant buildings to meet dose targets. By appropriately setting the location of the facility and the distance of key buildings from the site boundary, radiation exposure to the public can be reduced to negligible levels. Shielding integrated into transport vehicles or waste handling systems further reduces exposure to workers, which is controlled by appropriate monitoring equipment.

Components providing safety functions, summarised in Table 4.2-1, are broken down in terms of the relevant operational steps (as shown in Figure 4.2-6) in Table 4.2-2.

In addition to the facility design for the normal state, it is important to consider how abnormal states can be generated and the countermeasures required to provide defence in depth, as illustrated schematically in Figure 4.2-7.

Table 4.2-2 Attribution of requirements of containment and radiation shielding (HLW) to repository components

Safety functions and corresponding components		Containment during operation				Radiation shielding			
Operation process		Transport cask	HLW matrix (including fabrication canister)	Overpack	Waste reception/inspection & encapsulation facility	Transport cask	Waste reception/inspection & encapsulation facility	On-site transport vehicle	Emplacement machine
Surface facility	1. Transportation to surface facilities	✓	✓			✓			
	2. Acceptance and inspection of waste, temporary storage		✓		✓		✓		
	3. Encapsulation		✓		✓		✓		
	4. Loading on to transporter		✓	✓	✓		✓	✓	
Repository	5. Transportation underground		✓	✓	✓			✓	
	6. Transportation and emplacement in disposal tunnel		✓	✓	✓				✓
	7. Backfilling and sealing of disposal tunnels		✓	✓					

✓: Components ensuring the safety function

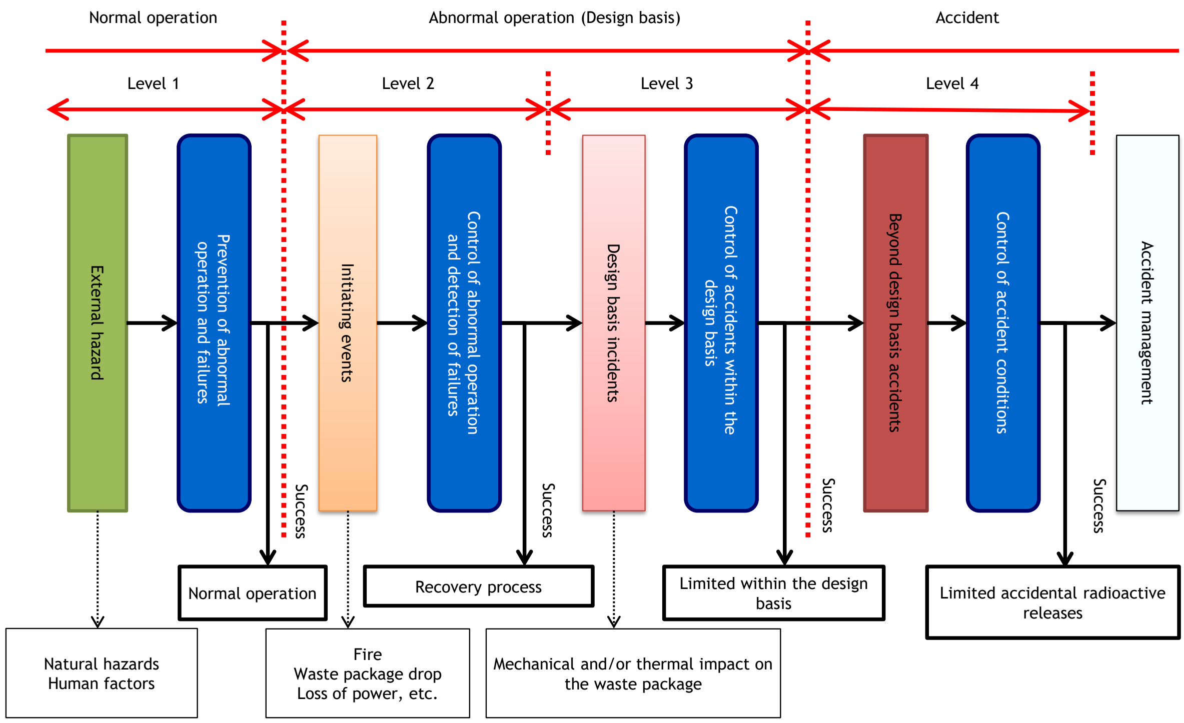


Figure 4.2-7 Abnormal state development and its relationship to safety measures (based on IAEA, 2005 [22], Nuclear Emergency Headquarters, 2011 [23])

In terms of design of facilities and operational processes, it is necessary to consider measures to prevent the occurrence of any significant abnormal events, together with measures to prevent the expansion of abnormal events that cannot be excluded, measures to mitigate resulting impacts, as well as any required recovery measures. Together these measures contribute to the resilience of the repository design, which has been identified as a key requirement following the Fukushima Daiichi accident (discussed further in Umeki et al., 2017 [24] [25]).

Initiating events that can lead to abnormal states during construction and operation of repositories include flooding, gas inflow, rock falls, etc., which are mainly related to general occupational safety. Although the concept of defence in depth/resilient design described was developed for radiation protection, it can also be applied for general occupational safety. If there is a need for recovery after incidents, this could also imply radiological considerations. In such cases an assessment would be needed to determine whether specific designs should be modified considering this aspect.

Table 4.2-3 summarises the relationship between safety functions and some components related to general occupational safety.

Table 4.2-3 Relationship between safety functions related to operational safety and main design components (modified from NUMO, 2011 [1])

Basic concept	Safety function		Components
Prevention of industrial accidents	Prevention of occurrence and propagation of incidents	Fire protection measures	Fire/smoke detection and fire-fighting equipment
		Mechanical stability of the tunnel	Support work: mesh/shotcrete/rock bolts, liners
		Additional accident prevention measures	Fall prevention devices, emergency water storage tank
	Evacuation routes established in case of emergency	Assuring alternative evacuation routes	Access shafts for air intake, connecting tunnels, emergency shelters, airlocks, communication equipment
Maintenance of healthy working environment	Maintain conditions appropriate to worker health and safety	Ventilation	Tunnel ventilation circuits, ventilation system (including cooling system and humidity control, if required)
		Drainage	Tunnel drainage path, drainage system
		Lighting	Primary and backup lighting equipment

This is subdivided in terms of the requirements to maintain a healthy working environment, building resilience by reducing risks and consequences of perturbations and assuring worker safety in the event that an accident occurs.

(2) Relationship of post-closure safety functions and repository components

(i) HLW

After closure, safety is assured by passive functions of HLW repository components, provided the disposal tunnels are backfilled and the repository is closed as intended in the design, as indicated in Table 4.2-4. The safety functions relating to isolation are predominantly provided by the geological setting (complemented by markers and/or record keeping to reduce the risk of inadvertent human intrusion): the key design feature here having an impact is the selected disposal depth, with greater depth generally providing more isolation. Safety functions related to containment can be influenced by design, and are split into those restricting RN release and those restricting subsequent migration to the biosphere. At early stages, various THMC processes will impact performance and these will be assessed in detail in future studies.

Table 4.2-4 Relationship between safety functions related to post-closure safety for HLW and main design components (modified from NUMO, 2011 [1])

Basic concept	Safety function		Component
Isolation	Protection from significant effects of natural perturbing phenomena		Geological environment
Isolation	Reduction of the likelihood of human intrusion		Geological environment/depth
Containment	Restriction of RN leaching	Prevention of contact between waste and groundwater	Overpack
		Low waste matrix dissolution	Glass matrix
	Restriction of RN migration	Low solubility of RNs	Geological/EBS environment
		Low migration rate due to slow groundwater flow	Geological environment
		Limit release from EBS by advection	Buffer
		Colloidal transfer inhibition	Buffer
		Sorption of RNs	Buffer Geological environment
		Dispersion of RNs	Geological environment
		Avoiding tunnels acting as short-circuit flow paths	Backfill/plugs

However, provided no major disturbances occur at early stages the key post-closure containment functions of the different repository components are:

○ EBS

- The HLW borosilicate glass matrix is highly stable and will leach only very slowly in contact with water, limiting releases of RNs. Under stagnant conditions, glass dissolution is associated with formation of secondary products, which will also incorporate some safety-relevant RNs. Radiolysis of water will occur, predominantly by alphas at glass/secondary product surfaces, potentially leading to net oxidising conditions.
- The overpack assures complete containment for the period in which the EBS shows evolving complex THMC conditions and has thus been designed to ensure that RN releases commence only when all trapped air is consumed, the buffer is fully saturated and all components are at rock ambient temperature. After failure, the overpack and its corrosion products will buffer any radiolytic oxidants produced within it and may

sorb/incorporate some released RNs. As loss of containment will probably be localised, the overpack may also act as a barrier to RN release to the inner side of the buffer.

- As the buffer material saturates with groundwater, it swells to form a homogeneous, plastic, low permeability, self-healing, microporous barrier that provides mechanical protection of the overpack, acts as a colloid filter and functions as a semi-permeable membrane. The buffer thus prevents significant advective flow and retards the diffusive transport of RNs.
- Retention within the EBS will mean that a large part of the total radioactivity inventory will decay within this zone and releases will be restricted to more mobile, long-lived RNs (and their decay daughters).

○ Backfill and plugs

- Repository access (ramps and shafts), connecting and disposal tunnels, and their associated excavation damaged zones, provide potential short-circuit flow paths after closure. This is prevented by tailoring tunnel layout in relation to hydraulic gradients and emplacement of appropriate backfill and plugs/seals.

○ Geological environment

- The large geological overburden effectively isolates the repository disposal panels from the biosphere, assuring that, after closure, even major surface perturbations have no impact on disposed waste. After loss of containment by the EBS, the slow flow of groundwater deep underground constrains subsequent migration, while the mineralogy of flow paths and the reducing chemical environment leads to restriction by sorption/precipitation of RNs. Even non-reactive RNs can be retarded by diffusion from advective flow paths into non-flowing matrix porosity. During transport through the geosphere barrier, concentrations of RNs are reduced by both decay and hydrodynamic dispersion.

(ii) TRU waste

For definitions of TRU waste groups, see Table 2.1-2 in Chapter 2. After closure, safety is assured by passive functions of the TRU waste repository components as indicated in Table 4.2-5. The isolation role is exactly the same as for HLW. As in the TRU-2 report, vaults for Grs.1 and 2 are assumed to include a buffer. The newly defined Gr.4H is also assumed to include a buffer due to its similarity to Gr.2 in terms of thermal output.

Table 4.2-5 Relationship between safety functions related to post-closure safety for TRU waste and main design components

Basic concept	Safety function		Waste Gr. 1	2	3	4L	4H	Component
Isolation	Protection from the significant effects of natural perturbing phenomena		✓	✓	✓	✓	✓	Geological environment
Isolation	Reduction of the likelihood of human intrusion		✓	✓	✓	✓	✓	Geological environment
Containment	Restriction of RN leaching			✓*3	✓			Waste matrix*1
Containment	Restriction of RN leaching		✓	✓*3	✓	✓	✓*3	Waste matrix*1
Containment	Restriction of RN leaching		✓	✓*3	✓	✓	✓*3	Waste package*2
Containment	Restriction of RN migration	Low solubility of RNs	✓	✓	✓	✓	✓	Geological environment
Containment	Restriction of RN migration	Low migration rate due to slow groundwater flow	✓	✓	✓	✓	✓	Geological environment
Containment	Restriction of RN migration	Limit release from EBS by advection	✓	✓			✓	Buffer
Containment	Restriction of RN migration	Colloidal transfer inhibition	✓	✓			✓	Buffer
Containment	Restriction of RN migration	Sorption of RNs	✓	✓			✓	Buffer
Containment	Restriction of RN migration	Sorption of RNs	✓	✓*3	✓	✓	✓*3	Infill
Containment	Restriction of RN migration	Sorption of RNs	✓	✓	✓	✓	✓	Geological environment
Containment	Restriction of RN migration	Dispersion of RNs	✓	✓	✓	✓	✓	Geological environment
Containment	Restriction of RN migration	Avoiding tunnels acting as short-circuit flow paths	✓	✓	✓	✓	✓	Backfill, plugs

✓Component to secure safety function in each waste group.

*1TRU waste is within a container or drum, which may prevent waste contact with groundwater for a period after closure.

*2Waste package B has a lid and hence waste contact with groundwater is prevented until this package fails.

*3This is heat-generating waste, and it is necessary to confirm possible thermal impacts on the safety function when developing the design.

Grs.1 and 4L have no buffer. Key containment functions of the different repository components are thus:

○ TRU waste EBS

- Some TRU waste streams have a matrix that limits RN release rates. This is particularly the case for Gr.2 metallic hulls and ends and Gr.3 bitumen. It is possible that conditioning will also limit release rates of other waste streams, but the associated knowledge base is limited.
- TRU waste is conditioned within sealed drums or metal containers, which will prevent RN release until they fail.
- The TRU waste disposal package B (see Section 4.2.3 (2) (ii)) will provide complete containment until it fails and, thereafter, like package A, may limit RN release by sorption onto corrosion products or package infill.

- After failure of containment, releases of RNs will be constrained by both restriction of groundwater flow by structural concrete and vault infill/backfill and also sorption onto these materials. The high pH environment assured by the large quantity of concrete also limits the solubility of some key RNs. It is possible that heat-emitting waste (Grs.2 and 4H) may cause thermal degradation of such properties.
- When buffer material is present, it saturates with groundwater and swells to form a homogeneous, plastic, low permeability, self-healing, microporous barrier that acts as a colloid filter and functions as a semi-permeable membrane. The buffer thus prevents significant advective flow and retards the diffusive transport of RNs.

○ Backfill and plugs

- As for HLW above.

○ Geological environment

- As for HLW above.

4.2.5 Features of the SDM relevant to repository design

The design of the repository is carried out based on the 3D SDMs for representative rocks developed in Chapter 3. The SDMs include structural, lithological and hydrogeological models, together with physical, mechanical and thermal characteristics of the host rock (see Table 4.2-6 below) and the chemical composition of groundwater required to develop repository design. Note that for the Pre-Neogene sediments, the coherent facies that was used to build the repository-scale hydrogeological model (Section 3.3.3 (4) (ii) (c)) was also used for the repository design.

Thermal properties of rock generally depend on porosity and water content, which can significantly alter these parameters [26]. In the H12 report, thermal conductivity and specific heat are defined by contributions of water, air and rock matrix given by their volumetric ratios, which is also assumed in this report. Based on data from Table 3.3-17, required thermal and mechanical property values have been derived and summarised in Supporting Report 4-2.

The uniaxial compressive strength can be used to define the rock stability index[3] for underground facilities. Low values of this parameter, especially for Neogene sediments, indicate the need to provide mechanical support for tunnels or locate the facility at a shallower depth.

[3] The stability index is an indicator used as a guide for setting rock stability and is obtained by dividing uniaxial compressive strength by initial stress. Generally, the smaller the value is, the more unstable a tunnel is. When the stability index is less than 2, it is considered that rock damage is likely to occur around the tunnel. (N.B.This footnote is not included in the Japanese version of the report.)

Table 4.2-6 Values of geological environment characteristics (physical, mechanical and thermal properties)

Rock type		Plutonic	Pre-Neogene	Neogene
Physical characteristics	Saturated density ρ (Mg/m^3)	2.69	2.64	2.28
	True density ρ_R (Mg/m^3)	2.7	2.7	2.7
	Effective porosity n_e (%)	0.8	3.5	25
Mechanical characteristics	Uniaxial compressive strength q_u (MPa)	115		15
	Modulus of elasticity E (MPa)	37,000		3,500
	Poisson's ratio υ (-)	0.25		0.3
	Cohesion intercept c (MPa)	15		3
	Internal friction angle φ (°)	45		28
	Tensile strength σ_t (MPa)	8		2.1
	Lateral pressure coefficient K_0 (-)	164/h + 0.74 (h: depth (m))		
	Initial vertical stress σ_v (MPa)	ρgh/1,000 (ρ: saturated density (Mg/m^3), g: gravitational acceleration (9.8 m/s^2), h: depth (m)		
	Initial horizontal stress σ_h (MPa)	$K_0\sigma_v$		
	Elastic wave (P wave) velocity V_p (km/s)	2.1 + 2.9 {1-exp (-0.00792 ρ_h)}		1.8 + 1.4 {1-exp (-0.00057 ρ_h)}
Thermal characteristics	Thermal conductivity λ (W/m K)	2.9	2.8	2.3
	Specific heat C(kJ/kg K)	1.0	1.0	1.4
	Geothermal gradient dT/dz (°C/100 m)	3		
	Mean surface temperature T (°C)	15		

Table 4.2-7 shows the hydrogeological characteristics (hydraulic conductivity) used in design, taken from repository-scale models (Section 3.3.3 (4) (ii)). Here, plutonic rocks are assigned a single lithology, while Neogene and Pre-Neogene sediments are assigned hydraulic conductivities for each of the main lithological units present in the SDM.

Table 4.2-7 Design data of geological environment characteristics (repository scale hydrogeological properties)

Rock type	Plutonic	Neogene	Pre-Neogene
Hydraulic conductivity (m/s)	2.7×10^{-8}	Upper mudstone layer: 2.0×10^{-9} Lower mudstone layer: 4.4×10^{-8} Sandstone layer: 5.3×10^{-7}	Sandstone dominant substrate: 2.0×10^{-9} Mudstone dominant substrate: 2.0×10^{-9} Chert rock mass: 1.0×10^{-8}

Reference groundwater chemistries for the 3 representative rocks are given in Table 3.3-16, presenting high salinity and low salinity variants for each (more information in Supporting

Report 3-31). In Table 4.2-8, the key chemical parameters for design are presented: pH, Eh, salinity, total inorganic carbon and sulphur species concentrations. The pH is in the range of 6.3 to 8.4, near neutral to weakly alkaline, with Eh in the reducing range of -170 to -300 mV, which would be favourable for minimising metal corrosion.

Table 4.2-8 Water chemistry used for repository design

Rock type	Plutonic		Neogene		Pre-Neogene	
Groundwater salinity	Low	High	Low	High	Low	High
Water T (°C)	45	45	30	30	45	45
pH	8.2	7.6	8.4	6.5	8.2	6.3
Eh (mV)	-300	-260	-280	-170	-290	-170
Cl concentration (proxy for salinity) (mol/l)						
Cl^-	2.3×10^{-3}	4.9×10^{-2}	1.1×10^{-3}	2.1×10^{-1}	1.1×10^{-3}	2.1×10^{-1}
Carbonate species concentration (mol/l)						
Total C	9.5×10^{-4}	2.2×10^{-4}	1.7×10^{-3}	4.0×10^{-2}	1.7×10^{-3}	4.7×10^{-2}
Sulphur species concentration (mol/l)						
H_2S	4.8×10^{-10}	2.8×10^{-9}	9.5×10^{-11}	1.4×10^{-9}	3.3×10^{-10}	4.7×10^{-9}
HS^-	1.3×10^{-8}	2.2×10^{-8}	2.9×10^{-9}	8.5×10^{-10}	8.7×10^{-9}	2.5×10^{-9}
SO_4^{2-}	6.9×10^{-6}	1.4×10^{-5}	1.2×10^{-4}	2.6×10^{-6}	1.2×10^{-4}	2.5×10^{-6}
$CaSO_4$	2.3×10^{-7}	5.8×10^{-6}	2.0×10^{-6}	8.1×10^{-8}	2.3×10^{-6}	8.5×10^{-8}
$NaSO_4^-$	1.3×10^{-7}	7.7×10^{-7}	2.1×10^{-6}	1.1×10^{-6}	2.1×10^{-6}	1.1×10^{-6}
$MgSO_4$	1.3×10^{-8}	6.7×10^{-8}	2.9×10^{-7}	3.0×10^{-7}	4.1×10^{-7}	4.0×10^{-7}

Even at its highest, the salinity is about a third of that of sea water, and thus lies within the range used during testing of overpack and buffer materials. In Table 4.2-8, the carbonate concentration is noted to allow assessing the passivation of the overpack carbon steel and evaluation of effects on local corrosion.

Carbonate concentrations between 2.2×10^{-4} and 4.7×10^{-2} mol/l lie within the range of, preferable geological environment characteristics, being below a specified upper limit of 0.5 mol/l (Table 3.1-2). Sulphur species concentration is used to assess microbial corrosion of metal.

4.3 Setting of repository depth

A key constraint on design of the EBS and underground facilities layout is the selected disposal depth. Clearly, the depth at which potential host formations are present at a site plays a key role but, in the following, it is assumed that this does not constrain choice (however this will need a thorough assessment during the PI stage). As a boundary condition for geological disposal, a clear legal requirement of a depth below surface of at least 300 m is defined. In addition, a further depth margin can be considered to account for the effects of uplift and erosion during the main evaluation period (100 ky), which would define a minimum depth.

As mentioned in Section 3.4.3, long-term uplift and erosion strongly depend on local topography, geology, tectonic conditions, etc., which can be considered quantitatively when a site is available. Thus, rather than conducting a detailed quantitative assessment of erosion, a rough estimate is made here using average data, showing that uplift rates in Japan generally lie in the range of 0 - 30 m in 100 ky (see Supporting Report 3-35).

Although risks of perturbation due to uplift and erosion decrease with increasing depth, this needs to be balanced against greater lithostatic and hydrostatic loads and higher ambient rock temperature, so choice of depth has to balance these conflicting requirements. For this reason, the maximum depth at which the HLW repository can be reasonably constructed is defined based on the design requirements shown in Table 4.3-1. Nevertheless, it should be recognised that hydraulic properties and hydro-geochemistry may also be depth dependent, and this would also be factored into final selection for actual sites.

Table 4.3-1 Design considerations for setting the HLW repository depth

Increasing repository depth: Influenced components and impacts		
Component	**Impact**	**Design considerations**
Tunnel	Lowering of the cavity stability due to the increase in rock stress	Ensuring the mechanical stability of the cavity with reasonable shoring (Supporting Report 4-3)
Buffer	Increase in the waste footprint due to the increase of rock temperature	For specified buffer temperature limit (100 °C), the waste package separation has to be increased as required (Supporting Report 4-14)
Ventilation system	Increase in ventilation capacity due to the increase of rock temperature	Ventilation equipment has to be specified to limit temperature in working areas as specified by Article 611 of the occupational health and safety regulations (37 °C)

Using Table 4.2-6 geological environment characteristics, reference depths of 1,000 m for plutonic rocks and Pre-Neogene sediments and 500 m for Neogene sediments was derived using the simple, rather conservative assessment for HLW disposal described in detail in Supporting Report 4-3. When selecting these depths, no specific consideration was made regarding potential differences between the siting environments sensitivity to erosion, but such considerations would certainly be made at real sites. Assuming co-disposal of HLW and TRU waste, both disposal zones are assumed to be at the same depth, although depths for each would be re-assessed independently based on conditions found at a specific site, using less conservative assumptions.

More factors (e.g. construction practicality, costs, thermal dimensioning and risk of human intrusion) than those considered above may need to be assessed in setting repository depth. The required approach has been developed, so that it can be applied on a site-specific basis.

4.4 EBS design

The basic safety requirements for the HLW and TRU waste repositories are noted in Section 4.1.1 and expanded upon to derive safety functions and the related design requirements of specific components of the EBS in Section 4.2.4. Here, detailed designs are developed based on these. In addition, their practicality is assessed based on the availability or development needs of technologies, with particular emphasis on manufacture/construction to required quality levels.

4.4.1 EBS for HLW

(1) EBS performance targets

HLW EBS components must meet both operational and post-closure safety functions (Table 4.2-1, Table 4.2-4), as indicated in Figure 4.4-1. The key EBS components, for the specified glass waste form and steel fabrication canister, are a long-lived overpack and a low permeability, plastic buffer that acts as a colloid filter.

Figure 4.4-1 EBS for HLW and illustration of some associated safety functions (adapted from NUMO, 2004 [2])

HLW is specified in Section 4.2.2 (1) as an EBS component, but properties are given by programme boundary conditions and hence not subject to design (although other components should prevent favourable HLW matrix properties from being degraded over relevant timescales). The overpack and buffer are designed on the basis of the specified shape, size, thermal output and radioactivity of the HLW canister. Also, as mentioned in Section 4.2.1, vertical H12V and horizontal PEM systems with the same overpack/buffer specifications are considered for the three defined SDMs.

(2) Overpack design

(i) Overpack design requirements and evaluation items

The overpack design requirements are shown in Table 4.4-1. The main safety functions of the overpack include prevention of leakage of RNs from waste during operations (Table 4.2-1) and prevention of release of RNs to groundwater for an extended period after closure (Table 4.2-4).

Table 4.4-1 Overpack design requirements

Design requirements	Objectives	Specifications
Low corrosion rate	The safety function to prevent waste from coming into contact with groundwater for a prescribed period of time after disposal is assured	Material, thickness, lid seal
Structural integrity	The safety function to prevent the waste from coming into contact with the groundwater is not impaired by the loads acting during operation and for a prescribed period after disposal	Material, thickness, shape, lid seal, lifting features
No radiation effects on corrosion rate	No significant acceleration of corrosion by radiation field	Material, thickness
Quality assured manufacture	Structure and materials that can be manufactured by existing technology or technology that will be realised in the near future	Material, shape
Remote handled HLW encapsulation	Processes and equipment capable of remote-handled encapsulation of HLW by existing technology or that which will be realised in the near future	Materials, dimensions, lid sealing concept
Remote-handled emplacement	Processes and equipment capable of remote handled overpack emplacement using existing technology or technology that will be realised in the near future	Shape, weight, lifting features (would not apply for PEM option)

To meet these safety functions, design requirements include: corrosion resistance, structural integrity and avoidance of radiation effects on corrosion. In addition, practicality of fabrication to required quality, remote-handled encapsulation and remote-handled emplacement are set as design requirements to meet the design factor “engineering practicality”. These design requirements are used to develop basic overpack specifications.

The period required to maintain the overpack containment is considered as follows. At early times after closure, HLW radioactivity and heat generation is large, and processes in the near field are complicated by coupled saturation, swelling and chemical reactions in the buffer. If RNs were released from the waste at this time, quantifying migration under these transient conditions would involve large uncertainties. Therefore, as in the H12 report, to simplify the assessment it is useful to assure complete containment during the period of significant heat output, which is taken to be about 1 ky (after which time the thermal output from HLW is only a few W/canister).

As indicated in Section 4.1.2, the impacts of loss of overpack function have to be considered in terms of performance of the entire system (coupling overpack design to that of other EBS components), both before (Chapter 5) and after closure (Chapter 6). Guidance on such coupling is provided by the Features Events and Processes (FEP) list (Section 6.2.1, Supporting Report 6-4), which identifies further issues to be considered, as shown in Table 4.4-2.

The resultant design specifications for the overpack include assurance of integrity in the event of localised buffer swelling, weld defects or earthquake ground motions. Additionally, the chemical impacts of high groundwater salinity and sodium in bentonite being exchanged by calcium have been considered in the design. The details of setting these design requirements and evaluation items are given in Supporting Report 4-4. Other potential impacts on how the EBS stability may be altered by unfavourable changes in the chemical environment are discussed in Chapter 6. If additional countermeasures against chemical impacts are required as a result of the performance assessment (Chapter 6), these will be further considered in the light of more detailed understanding of the evolving groundwater chemistry at specific sites.

Table 4.4-2 Overpack evaluation items considered in this report

Evaluation item	Objectives
Structural integrity in case of uneven buffer swelling	Load caused by uneven swelling of buffer material due to variable water content and uneven expansion of corrosion products does not impair structural integrity
Structural integrity in case of weld defects	The presence of weld defects does not compromise structural integrity
Structural integrity against earthquakes	Structural integrity is not impaired even for large-scale earthquake motions

(ii) Setting of overpack material, shape and inner dimensions

The overpack design and the exact specification of overpack material, shape and dimensions can only be decided when a specific repository concept has been selected. However, to illustrate the design steps involved, this study focuses on a steel overpack for a single HLW canister, with a bentonite/crushed rock buffer. Although copper and titanium were considered as alternative materials in the H12 report [6] [27], carbon steel is chosen here as the reference case due to the large knowledge base for this material. Furthermore, with a focus on ease of assuring structural integrity, fabrication by carbon steel forging (SF) that meets the relevant Japanese standard (JIS G 3201) is selected, with a specification (SF340A) that facilitates welding with a low risk of cracking. As described further in Section 4.4.1 (2) (viii), technological development is ongoing to confirm practicality of manufacturing and welding this material to required quality levels. It should be noted here that selection of welding as a sealing technique for the reference concept is again based on significant industrial experience. It may be, however, as sites are gradually narrowed down and a final concept is selected, that other options may be considered.

The shape of the overpack is taken to be cylindrical, from the viewpoint of the cylindrical shape of the HLW canister and structural integrity considerations. Furthermore, from the dimensions of the canister (diameter 430 mm × height 1,340 mm) and considering fabrication accuracy and remote handled encapsulation, the inner overpack dimensions are currently set as diameter 440 mm and height 1,350 mm.

(iii) Setting overpack thickness

In the H12 report, the thickness of the carbon steel overpack is set to 190 mm regardless of the geological environment [6]. In this report, the required thickness of the overpack is re-evaluated. Table 4.4-1 indicates how overpack thickness contributions to corrosion resistance, structural integrity and radiation shielding can be evaluated, based on the process shown in Figure 4.4-2.

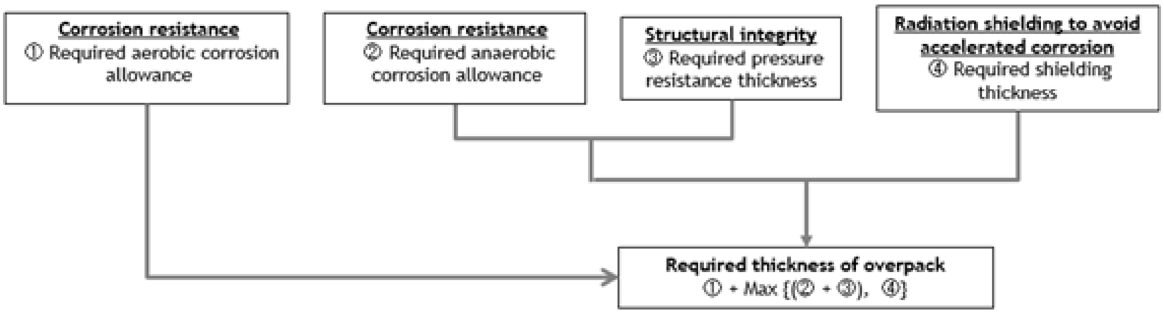


Figure 4.4-2 Setting overpack thickness

In the evaluation of corrosion resistance, stress corrosion cracking (SCC), hydrogen embrittlement cracking and microbial corrosion are also explicitly considered. Further details of the approach to setting thickness are provided in Supporting Report 4-5.

(a) Corrosion resistance

Environmental conditions that affect overpack corrosion include temperature, redox conditions and groundwater chemistry. The saturated buffer is expected to provide an isotropic compressive stress field and limit microbial activity, both of which are favourable for overpack longevity.

Section 4.5 sets a limiting buffer temperature of 100 °C (which relates to past simplistic assumptions and does not relate to current best-estimates to assure negligible alteration), which will relatively quickly decrease towards rock ambient. Similarly, initial trapped air will be rapidly consumed by reaction with the overpack, or minerals in buffer or host rock, to give a reducing environment. Groundwater chemistry (Table 3.3-16) will be changed by reaction with buffer minerals to produce the porewater chemistry in contact with the overpack (see Supporting Report 6-5), which is shown in Table 4.4-3.

Table 4.4-3 Buffer pore water chemistry components considered relevant to carbon steel corrosion

Rock type	Plutonic		Neogene		Pre-Neogene	
Groundwater salinity	Low	High	Low	High	Low	High
pH	7.2 to 9.6	7.1 to 8.4	7.2 to 9.8	6.3 to 6.5	7.1 to 9.6	6.1 to 6.3
Eh (function of pH) (mV)	-4.1×10^2 to -2.0×10^2	-3.2×10^2 to -2.0×10^2	-3.9×10^2 to -1.9×10^2	-1.7×10^2 to -1.4×10^2	-4.0×10^2 to -2.0×10^2	-1.7×10^2 to -1.4×10^2
Cl^- (mol/l)	2.3×10^{-3} to 4.5×10^{-3}	4.9×10^{-2} to 5.1×10^{-2}	1.1×10^{-3} to 3.3×10^{-3}	2.1×10^{-1}	1.1×10^{-3} to 3.3×10^{-3}	2.1×10^{-1}
Inorganic carbon concentration (mol/l)	9.6×10^{-4} to 7.9×10^{-3}	1.2×10^{-4} to 4.6×10^{-3}	1.6×10^{-3} to 9.1×10^{-3}	3.1×10^{-2} to 4.0×10^{-2}	1.7×10^{-3} to 8.6×10^{-3}	3.6×10^{-2} to 4.7×10^{-2}

More information on the calculation of pore water composition is provided in Supporting Report 6-15. Carbonate concentrations lie in the range of 1×10^{-4} to 5×10^{-2} mol/l which, together with relevant pH values, are used for the examination of sensitivity to SCC. Salinities lie in the range 1×10^{-3} to 2×10^{-1} mol/l, which is taken into account when assessing the results of corrosion tests. Where there is the potential for microbial activity in the buffer, the concentration of sulphur species may also be important.

For corrosion in the oxidising environment immediately after disposal, as in the H12 report, an average corrosion depth is calculated assuming that all oxygen remaining in the near-field rock, the buffer and backfill is consumed by corrosion (certainly over-conservative for the PEM case). This assumes that no oxygen can reach the overpack from the open tunnel system. From this, the maximum corrosion depth was estimated based on extreme value statistical analysis of corrosion data. From the analysis described in Supporting Report 4-6, based on the tunnel geometry given in Section 4.5.2, maximum corrosion depths of 5 to12 mm are derived, as shown in Table 4.4-4. Future consideration of actual knowledge and uncertainties will allow more realistic estimates of such corrosion to be derived, which may be significantly smaller.

Table 4.4-4 Required carbon steel overpack minimum thickness for 1 ky lifetime (units in mm)

Conditions			1 Corrosion allowance for the initial oxidising environment	2 Long-term corrosion allowance for reducing conditions	3 Pressure resistance	4 Required shielding	Overpack Required thickness = 1 + Max {(2 + 3), 4}
Rock	Emplacement method	Part					
Plutonic and Pre-Neogene	H12V	Flat	11	6	104	80	121
		Cylindrical	11	6	44	80	91
	PEM	Flat	5	6	104	80	115
		Cylindrical	5	6	44	80	85
Neogene	H12V	Flat	12	6	78	80	96
		Cylindrical	12	6	25	80	92
	PEM	Flat	5	6	78	80	89
		Cylindrical	5	6	2	80	85

Steel corrosion under anaerobic conditions in buffer saturated with artificial seawater (pH 8.5, NaCl: 5.6 × 10^{-1} mol/l, $NaHCO_3$: 2.4 × 10^{-3} mol/l) or artificial fresh water (pH 8.5, NaCl: 2.5 × 10^{-3} mol/l, $NaHCO_3$: 2.5 × 10^{-3} mol/l) has been measured for timescales of around a decade [28]. The average corrosion rates measured initially decreased over time regardless of salinity, which is consistent with the observed surface films caused by precipitation of secondary minerals such as iron carbonate (siderite) [28] [29]. However, as shown in Figure 4.4-3, the average depth of corrosion increased approximately linearly with time after 1 year, in all cases, yielding average corrosion rates of 2 μm/y or less [28], but there is also potential for localised corrosion that must be considered.

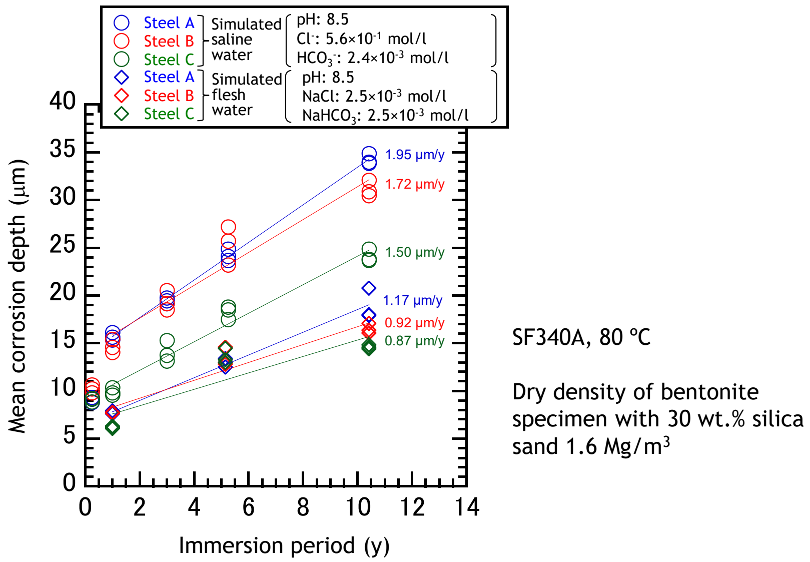


Figure 4.4-3 Evolution of the average corrosion depth of the carbon steel in buffer material under an anaerobic environment [28][4]

[4] In the literature [28], corrosion tests using a base material SF340A for tests of TIG (Tungsten Inert Gas) welding, electron beam welding and MAG welding are reported. Here, they were noted as base materials A, B, and C, respectively.

Based on this result, the average corrosion rate was set as 2 μm/y, independent of rock type, equivalent to 2 mm over the reference 1 ky period. Furthermore, considering potential uneven corrosion in this environment a maximum pitting factor was selected [30], leading to a maximum corrosion depth of 6 mm. This corrosion allowance is shown in Table 4.4-4. More details of the calculation and assumptions are given in Supporting Report 4-7.

SCC and hydrogen embrittlement cracking are phenomena that could potentially cause early failure of containment. These depend on stress conditions, material properties and environmental conditions – in particular temperature and water chemistry [31]. As SCC results from tensile stress, removal of residual stress by heat treatment after manufacture will be carried out, but there is a possibility that tensile stress may remain following welding of the lid. Thus, Section 4.4.1 (2) (viii) describes welding options that also include subsequent heat treatment, which should greatly reduce any residual tensile stress and assure that the overpack is subject to a predominantly compressive stress field.

Impacts of SCC and hydrogen embrittlement on the overpack are assessed in detail in Supporting Report 4-8. Relevant SCC forms are those that occur (1) at high pH and high carbonate concentrations; (2) at near neutral pH and low carbonate concentrations [32]; (3) associated with pitting/crevice corrosion of passivated steel at high salinities. Based on chemical constraints alone, as set by the porewater chemistries shown in Table 4.4-3, SCC forms (1) and (3) can be confidently excluded for relevant carbon steel, although the high tensile stresses required are also very unlikely. For near-neutral pH SCC, pore-water chemistry is marginal (pH tending to be too high) and again residual tensile stresses are expected to be too low. Thus, SCC is not considered a threat for carbon steel in compacted bentonite but, in any case, heat treatment after welding is planned.

Hydrogen embrittlement cracking may occur when hydrogen generated by carbon steel corrosion is absorbed and diffuses into the steel at a high enough concentration [6]. This process occurs predominantly in high strength steel and, for the more vulnerable welds, tensile strength is low enough that a relatively high diffusible hydrogen concentration is required (several ppm or higher), which is well above the values measured under relevant conditions and hence hydrogen embrittlement cracking is considered unlikely.

In addition, microbial activity can influence corrosion of steel [33]. Section 4.4.1 (3) (iii) indicates that microbial activity is low in buffer material having a dry density above 0.56 Mg/m^3, a situation expected to be maintained as long as the initially installed buffer density does not decrease too much [34]. Therefore, the probability of significant microbial activity on the overpack surface is considered low. However, considering that other studies [35] suggest much higher limits, work on this issue continues. Based on the more detailed assessment in Supporting Report 4-9, regardless of the microbial activity level, limitations in the supply rate of oxidants that can be used by microbes to catalyse corrosion (e.g. sulphate) in this hyper-oligotrophic environment result in total corrosion that is expected to be negligible compared to inorganic processes. Nevertheless, the activity of microorganisms in buffer materials is still being evaluated [35] and impacts will be reassessed in the future.

(b) Structural integrity

As the buffer re-saturates and swells, resultant pressure will add to the groundwater hydrostatic pressure. Furthermore, buffer deformation will result from corrosive expansion of the overpack together with rock creep (for soft rocks), with the combined force (referred to as the compaction reaction force) considered to act on the overpack. As discussed in detail in

Supporting Report 4-10, the combination of these loads results in a calculated external pressure acting on the overpack of 10.7 MPa for plutonic rocks and Neogene sediments (depth 1,000 m), and 6.8 MPa for Neogene sediments (depth 500 m). The required thickness to withstand these external pressures is set very conservatively using nuclear power plant standards [36], specifically as applied to class MC containers. As a result, the thickness required for structural stability is set for both the flat ends and the cylindrical body as 78 to 104 mm and 25 to 44 mm respectively, as shown in Table 4.4-4.

(c) Prevention of radiation effects on corrosion

Oxidising species, such as hydrogen peroxide, may be generated by the radiolysis of water due to penetrating radiation from the HLW. Corrosion tests of carbon steel in artificial seawater and low oxygen concentrations have been carried out to determine the impact of γ-irradiation [38] [39] [40]. Significant corrosion rate acceleration is observed only at doses above 3 Gy/h. Thus, a shielding margin is specified such that the absorbed dose rate of the overpack surface is equal to or less than 3 Gy/h. On the basis of a very conservative shielding analysis, the required shielding thickness was set to 80 mm (Supporting Report 4-11). However, it is recognised that more realistic analyses (e.g. taking into account decreases in radiation dose with time) could reduce this thickness significantly.

(d) Overpack thickness

Based on the above results, the procedure for setting the required thickness of the overpack in accordance with Figure 4.4-2 is summarised in Table 4.4-4. The required thickness of the overpack to assure 1 ky lifetime, even for the worst case plutonic H12V system, is a minimum of 121 mm. However, the thickness of the overpack is set to the H12 value of 190 mm, defined to cover all emplacement methods and both the lid and the cylindrical body with a large safety margin, although this could be rationalised in the future. As noted previously, the dimensions provided in this study are not optimised with respect to requirements, and especially not adapted for site-specific conditions. However, this will be a topic for future R & D.

(iv) Design of the overpack lid

As indicated in Table 4.4-1, the lid seal is relevant in terms of corrosion resistance and structural integrity. Two basic lid designs are currently considered, a drop-lid type and a flat type, as illustrated in Figure 4.4-4. Here the focus is on a drop lid structure. However, in the future, other designs, and even replacement of welding with a screw lid design could be possible.

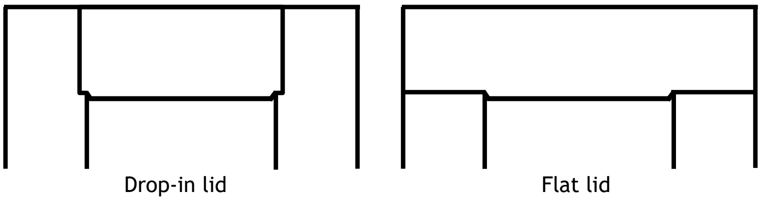


Figure 4.4-4 Schematic diagram of the lid structure

To set the weld depth, this was examined from the points of view of both corrosion resistance and structural integrity. Incidentally, with this lid structure, radiation is shielded by the base material peripheral to the weld and hence it is not necessary to set a radiation shielding margin for the weld itself (Figure 4.4-5).

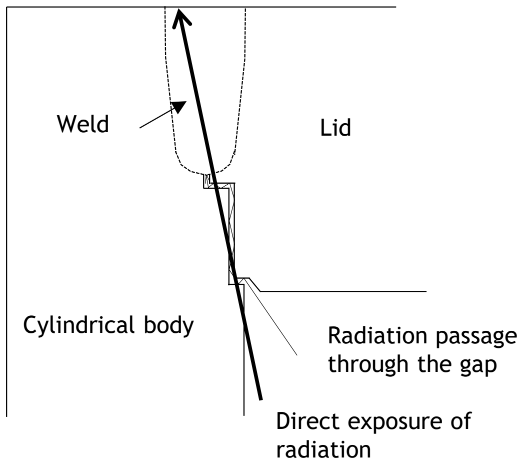


Figure 4.4-5 shielding of radiation around the weld

(a) Corrosion resistance

Under aerobic conditions, the corrosion behaviour of the weld is expected to be the same as that of base material in the case of Electron Beam Welding (EBW), which does not use any welding rods. For other methods that use some kind of welding rod, such as TIG (Tungsten Inert Gas) or MAG (Metal Active Gas) welding, the phenomenon of selective corrosion of the weld compared to the base material has been observed [41] [42]. However, it has been confirmed that the use of an improved Ni doped welding material has the effect of restricting such corrosion [43].

For long-term anaerobic corrosion, the average corrosion rate of welds in a reducing environment has been measured for immersion periods of up to 10 years in fresh and saline solutions, confirming that there is no significant difference in the corrosion behaviour of the weld and the base material [28] [37]. Thus, from Table 4.4-4, the sum of corrosion under oxidising and reducing conditions lies in the range of 11 to 18 mm in 1 ky.

Section 4.4.1 (2) (viii) defines the size limit for detection of weld defects as 2 to 3 mm. To account for the fact that an undetectable weld defect may be present, the required corrosion allowance of the base material is increased by 3 mm and thus the required corrosion allowance of the weld was set to between 14 and 21 mm.

(b) Structural integrity

The minimum weld depth is required to ensure that structural integrity is not impaired by loads acting during operation and after disposal, which are assessed in detail in Supporting Report 4-10 for the dominant post-closure loads summarised in Section 4.4.1(2) (iii) (b). Based on this shear stress, the required welding depth was conservatively set by applying the allowable shear stress specified in the rules on design and construction for nuclear power plants [36]. The resulting minimum weld depths are 20 mm for plutonic rocks and Pre-Neogene sediments and 12 mm for Neogene sediments.

(c) Setting the welding depth

As summarised in Table 4.4-5 summing the requirements gives minimum weld depths of 26 to 40 mm.

Table 4.4-5 Required minimum weld depth (mm) for the overpack

Conditions		1 Corrosion allowance for the initial oxidising environment	2 Long-term corrosion allowance for reducing conditions	3 Consideration of welding defects	4 Pressure resistance	Required welding depth = 1 + 2 + 3 + 4
Rock type	Emplacement method					
Plutonic and Pre-Neogene	H12V	11	6	3	20	40
	PEM	5	6	3	20	34
Neogene	H12	12	6	3	12	33
	PEM	5	6	3	12	26

Nevertheless, as in the H12 report, this parameter was conservatively set to the full overpack thickness. Therefore, rationalisation of welding depth is possible in the future.

(v) Design of the overpack lifting feature

The grip of the overpack shown in Figure 4.4-6 is based on the H12 and past studies [44], with the height of the grip portion given as 150 mm. This design will be revisited in the future, but it has little significance for the present safety case.

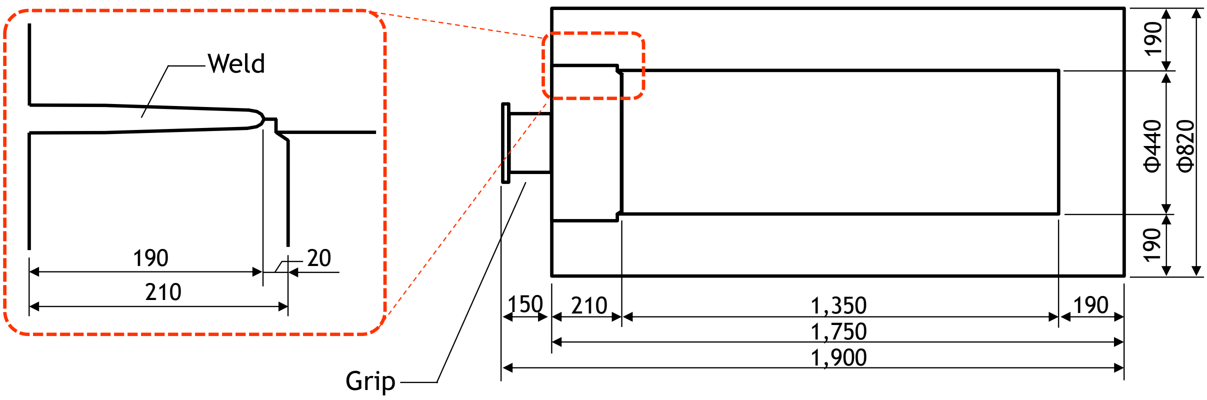


Figure 4.4-6 Overpack specification

(vi) Overpack specifications

Based on the above study, the overpack specification illustrated in Figure 4.4-6 is assumed to apply for both disposal concepts and the 3 representative host rocks.

(vii) Evaluation of overpack integrity

In Table 4.4-2, further evaluation items to assure overpack integrity were noted, including stability in the case of uneven buffer swelling, seismic motion and weld defects.

The net stress acting on the overpack is the sum of those resulting from expansion of corrosion products, hydrostatic load/rock creep and swelling of the buffer. Particularly in the case of uneven wetting of the buffer at early times, this could potentially lead to a bending force acting on the overpack, which could be a cause for SCC. On the basis of the extreme case of an uneven load on the overpack, evaluation results show that the plasticised zone does not extend through the overpack and hence mechanical failure will not occur [6]. For the PEM case, this phenomenon can potentially be prevented by including an outer geotextile layer, as demonstrated in the FEBEX mock-up [45].

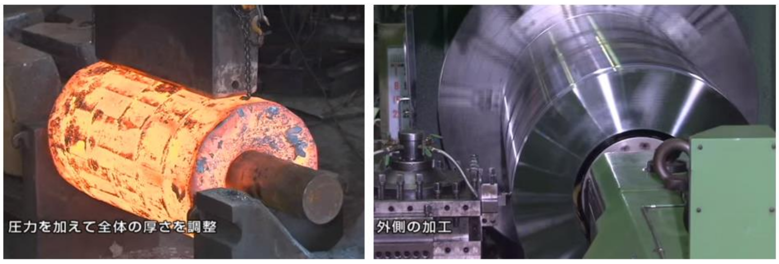
Impacts of seismic motion are considered in Section 4.4.1 (3) (iv), with a focus on stability of the buffer. From this analysis (described in detail in Supporting Report 4-17), the maximum stress acting on the overpack is only on the order of 1% for the yield strength and hence the risk of damage is negligible [46] [47]. In addition, the impact of secondary fractures moving as a result of the seismic motion has been considered (Section 4.4.1 (3) (iv)), but this can be mitigated by selecting a sufficiently plastic buffer.

As assessed in detail in Supporting Report 4-12, the effect of weld defects on structural integrity can be evaluated by consideration of welding residual stress and external forces acting on the overpack. Conservatively assuming decreased fracture toughness due to embrittlement, the allowable defect size that still ensures mechanical stability is 55 mm, reduced by a 10-fold safety factor to 5 mm. Therefore, since Section 4.4.1 (2) (viii) argues that non-destructive inspection techniques can detect defects of 2 to 3 mm or more, any defect $> \approx 5$ mm would certainly be picked up by weld inspection and hence this should not be a concern. Because of the huge degree of conservatism involved, more realistic assessment of maximum expected defect size would be useful to provide guidance on the response in terms of repair or overpack replacement in the event that small defects over the 5 mm limit are found.

Based on the assessment above, it was concluded that the structural integrity of the overpack was not threatened by any of these evaluation items.

(viii) Overpack production

The fundamental practicality of production of the overpack as specified in Figure 4.4-6 has been confirmed by state-of-the-art fabrication demonstrations [6] [48]. Figure 4.4-7 illustrates full-scale fabrication of the overpack by forging [49] [50].



(a) Forging (b) Machining

(c) Produced cylindrical body and drop-in lid

Figure 4.4-7 Production of a carbon steel overpack by forging (Source: (a), (b) [49]; (c) [50])

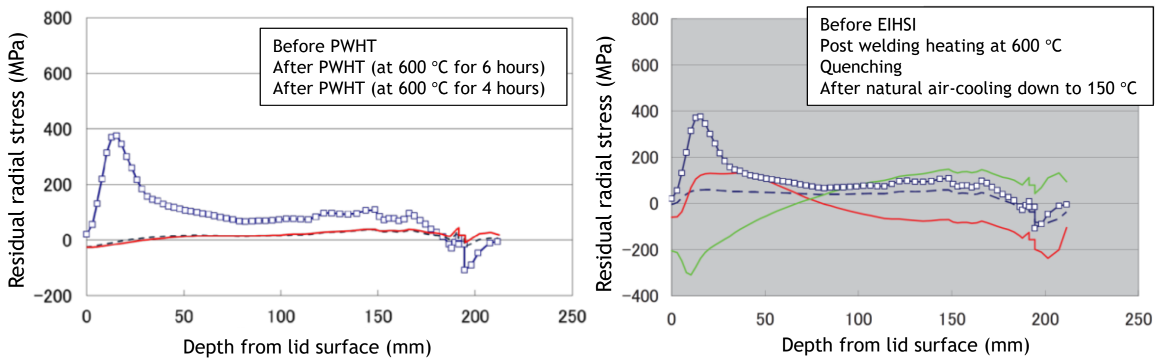
In terms of welding the lid, full-scale demonstrations of TIG (Figure 4.4-8), MAG and electron beam welding have been carried out. Here, TIG welding is described, which has been confirmed to be able to be produce a defect-free 190 mm weld of a drop lid structure [51].

(a) Welding process (b) Weld bead appearance (c) Weld cross-section

Figure 4.4-8 TIG welding test (Source: [51])

The time required for welding the lid is between 24 and 33 hours, although this can be significantly reduced by using up to four torches simultaneously [20]. For the design of the surface facilities in Section 4.6, TIG welding of lids is assumed. In terms of alternative welding options, a fusion failure occurred at the bottom of the lid gap in the full-scale test of MAG welding [52]. To consider adopting this method, it would be necessary in the future to develop technology to improve quality by optimising the welding conditions. For electron beam welding, it has been confirmed that welds of up to 80 mm are possible for the drop lid structure [53]. As described in Section 4.4.1 (2) (iv) (c), the actual required welding depth is between 26 and 40 mm, so electron beam welding could also be applicable.

Section 4.4.1 (2) (iii) (a) noted that, since the environmental conditions for near-neutral SCC cannot be precluded, reduction of the weld residual tensile stress would be beneficial. Post-Weld Heat Treatment (PWHT) and External Induction Heating Stress Improvement (EIHSI) can provide such residual stress reduction, as shown in Figure 4.4-9 [44] [54].



(a) Example of residual stress reduction by PWHT

(b) Example of residual stress reduction by EIHSI

Figure 4.4-9 Residual stress reduction examples ((a) [54], (b) [43])

According to the results, in the corrosion allowance layer (14 to 21 mm from the surface), the tensile residual stress (up to about 390 MPa in the overpack radial direction) occurring before the post heat treatment can be reduced in the case of PWHT to about -30 MPa, whereas in the case of EIHSI, this is converted to compressive stress field of about -330 to -200 MPa. It can be noted that the temperature involved for heat treatment (~ 600 °C) [54] lies below that at which devitrification of HLW is a concern [55] [56].

With regard to inspection technology for weld defects, confirmation of the applicability of ultrasonic flaw detection to welds with a depth of 190 mm is in progress. Based on confirmation by destructive testing, ultrasonic tests detected defects with size 2 to 3 mm or more with ≈ 100% efficiency in the weld with 190 mm deep [57].

(ix) Period over which overpack safety functions are assured

From the above, the overpack thickness of 190 mm specified is about 70 mm above that required to maintain the function of the overpack to prevent contact waste and groundwater for 1 ky (in the worst case of H12V in plutonic rock this is 121 mm – see Table 4.4-4). As discussed in detail in Supporting Report 4-13, the earliest estimated time to overpack failure was approximately 17,000 years. However, since the assessed lifetime is much longer than that required, there may be room for optimising the overpack design, although such optimisation must consider the performance of the other barriers as well. Modifications of the design will be carried out in future steps of the repository development programme.

(3) Buffer design

As for the overpack, this section is based on the H12 design. It is understood that these designs may be modified in future NUMO design work.

(i) Design requirements and evaluation items for the buffer

The design requirements for HLW buffer which assure the safety functions (as discussed in Section 4.2-4) are shown in Table 4.4-6. These result from an assessment (in Supporting Report 4-14) of top-level requirements for limiting RN release, inhibiting colloid migration and limiting RN transport.

Table 4.4-6 Design requirements for the HLW buffer

Design requirements	Objectives	Specifications
Low permeability	Restricting groundwater advection in the buffer, reducing overpack corrosion and restricting transport of RNs	Material, effective clay dry density
Colloidal filtration capacity	Preventing RN migration in a colloidal phase	Material, effective clay dry density
Self-sealing	Sufficient swelling to fill any gaps left after construction	Material, effective clay dry density, thickness
Self-healing	Ability to close any openings generated after emplacement, e.g. due to gas breakthrough	Material, effective clay dry density
Engineering practicality	Ability to manufacture and install to required quality levels based on existing technologies or those reasonably expected in the near future	Material, effective clay dry density, fabrication plan
Prevention of microbial effects	Suppressing microbial activity in buffer material that could increase overpack corrosion	Material, effective clay dry density
Physical buffer	Sufficient plasticity to protect the overpack by reducing the impact of mechanical perturbations	Material, effective clay dry density, thickness

Requirements important for post-closure safety can be broken down into direct buffer design requirements for low permeability, colloidal filtration, self-sealing (closing of original gaps), self-healing (closing of gaps after perturbation of the buffer), RN sorption, etc. Furthermore, in addition to those that contribute to overpack design requirements, such as limitation of microbial activity and physical buffering, design requirements necessary to ensure engineering practicality have to be added. The buffer material selection, design (geometry, thickness) and emplacement concept are then developed on the basis of these design requirements.

As was the case for the overpack (Section 4.4.1 (2) (i)), the impacts of buffer loss of function have to be considered in terms of performance of the entire disposal system (coupling buffer design to that of other EBS components), both before (Chapter 5) and after closure (Chapter 6). Guidance on such coupling is again provided by the FEP list (Section 6.2.1, Supporting Report 6-4), which identifies further issues to be considered, such as those shown in Table 4.4-7.

Table 4.4-7 Evaluation items for HLW buffer in the current assessment

Evaluation item	Objectives
Mechanical stability during evolution of the EBS	Demonstration that long-term evolution of stresses due to corrosion, weight of the overpack and creep of rock does not significantly degrade the required functions of the buffer
Mechanical stability in the event of earthquakes	Demonstration that overpack and buffer do not lose mechanical stability in the event of large-scale earthquake motions

For example, the effect on the buffer due to heat from the waste is considered during repository depth selection in Section 4.3 and tunnel design requirements in Section 4.5.2 (1). From the standpoint of assuring long-term performance of both overpack and buffer, the evaluation items specified focus on mechanical stability, both in terms of evolution of the EBS and impacts of major earthquakes. More information about these design requirements and evaluation items is given in Supporting Report 4-14.

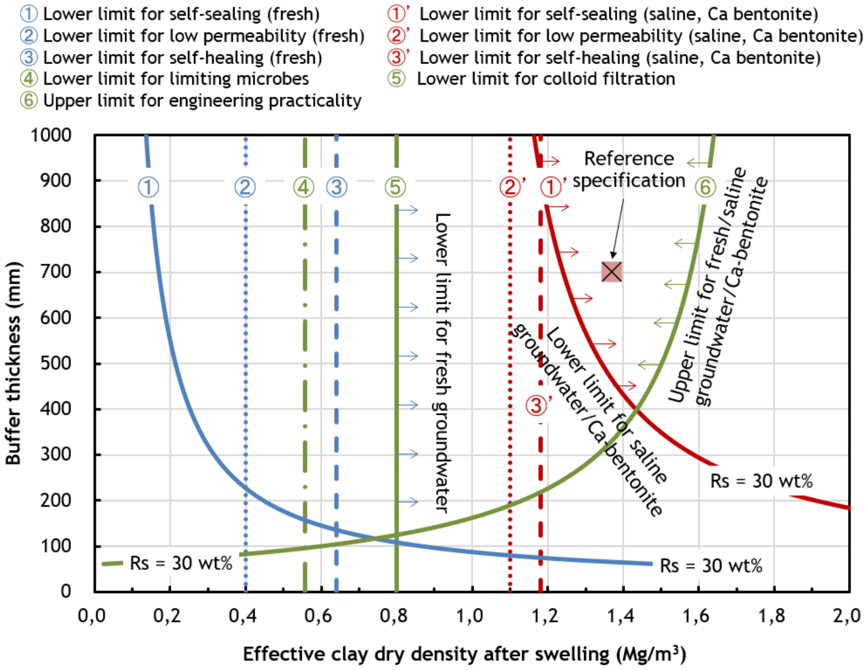
(ii) Choice of buffer material

Compacted bentonite is selected as a material that can satisfy all buffer requirements for the range of siting conditions assessed. A number of bentonites of different origins and properties have been studied [58]. Kunigel V1, which is a Na-type bentonite, has been well investigated in Japan and therefore selected as the buffer material for the reference specification. The permeability and swelling properties of bentonite are affected by the salinity of groundwater. As shown in Table 4.2-8, salinities in the model groundwater range from 1×10^{-3} to 2×10^{-1} mol/l, and thus, both "fresh" and "saline" conditions are considered when setting the buffer specifications. Also, due to the diffusion of Ca from groundwater and concrete present in the disposal tunnel, exchangeable Na ions may be replaced with Ca ions, causing the initial performance to degrade with time. In this report, it is conservatively assumed that this conversion may occur; however this assumption may be reassessed with a more detailed analysis in the future if conversion to Ca bentonite is shown to have a large impact on performance.

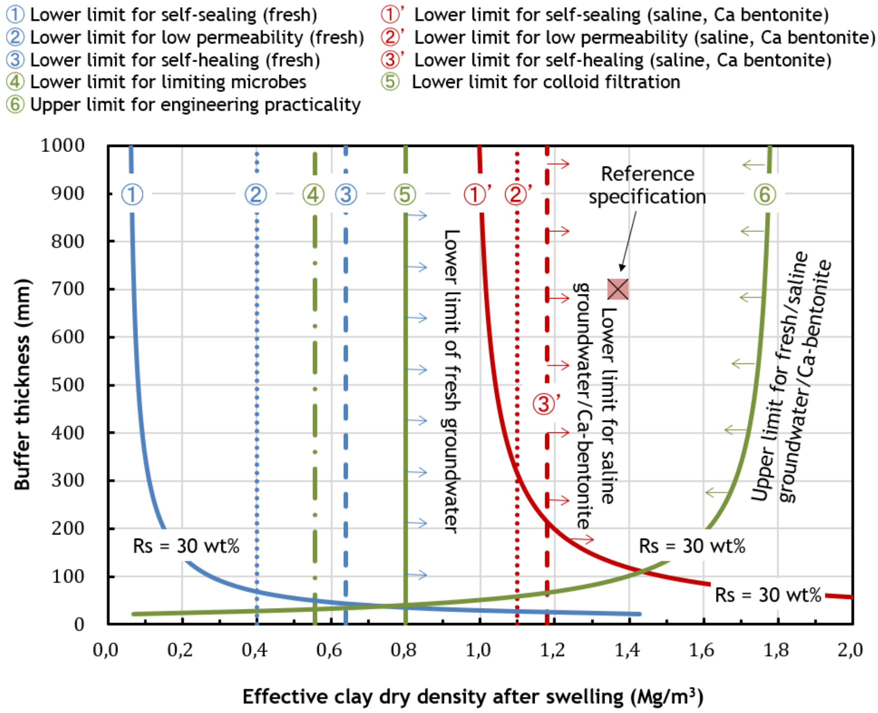
In addition, with regard to the composition of the buffer material, the H12 report considers mixing of silica sand with bentonite. Such a mixture tends to lower the swelling pressure, but is advantageous in terms of compaction characteristics, thermal conductivity, resistance to erosion, cost, etc. [59] [60]. However, this will be studied further and other compositions may also be considered in the future.

(iii) Setting the density and thickness of the buffer

Design requirements to assure buffer performance (see Table 4.4-6) are effective clay dry density (i.e. the dry weight of bentonite per unit of buffer) and thickness, for fresh and saline conditions, which are tailored to H12V and PEM concepts, as illustrated in Figure 4.4-10 and described in more detail in Supporting Report 4-15.



(a) H12V



(b) PEM

Figure 4.4-10 Specification ranges of buffer for current basic design requirements (Rs is the silica sand content)

Here, Figure 4.4-10 plots performance objectives as a function of effective dry density of clay and buffer thickness, assuming swelling clay fills any gaps left after buffer emplacement.

A gap of 40 mm was assumed between rock and buffer, and 20 mm between buffer and overpack in the H12V case, while only the latter was assumed in the case of the PEM[5].

To conservatively assess impacts of ionic strength, salinities up to that of seawater were considered. In the formulation of the buffer, the mixing ratio of silica sand (Rs) was set to 30% by weight on the basis of ability to produce high quality compacted blocks [61] (see Section 4.4.1 (3) (v) (a)), while also ensuring that other requirements were met. The effective clay dry density, used as an index of the buffer specification, is the dry density of bentonite in the bentonite/sand mixture. It should be noted that the relation between effective clay dry density and properties depends on the type of bentonite. Curves and relationships presented in this chapter are for Kunigel V1, unless otherwise stated.

From Figure 4.4-10, the specification of effective clay dry density established for freshwater conditions has to be above the design requirement ⑤ (lower limit of colloidal filtration) and below ⑥ (upper limit for engineering practicality. For saline conditions (or Ca-type of bentonite, as shown in Figure. 4.4-11), the range lies again below ⑥ but with the lower limit either set by either ① (lower limit of assured self-sealing) or ③ (lower limit of assured self-healing), depending on thickness.

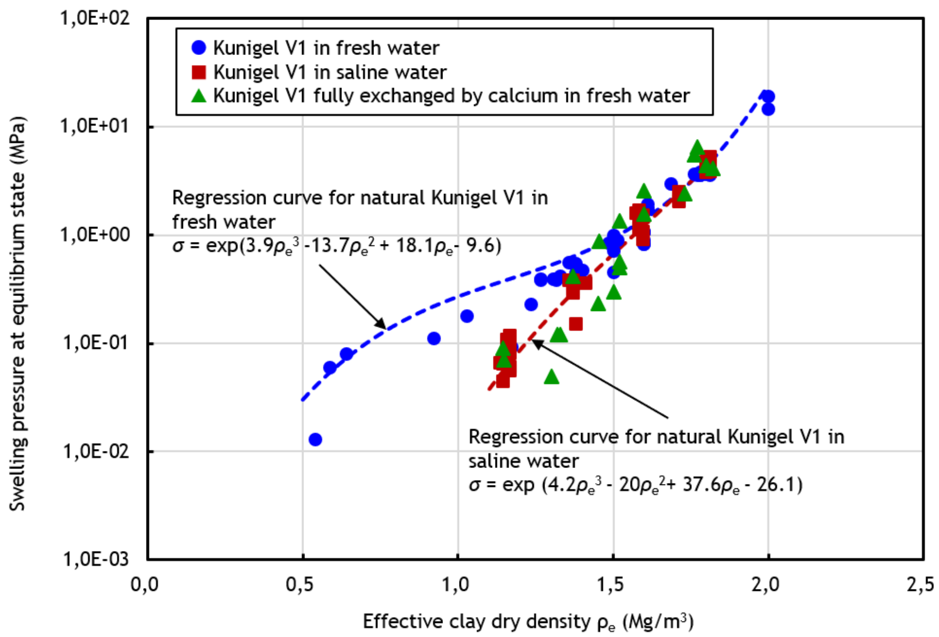


Figure 4.4-11 Relationship between effective clay dry density and the equilibrium swelling pressure of bentonite (from Suzuki et al., 1992 [62], Maeda et al., 1998 [63], Suzuki & Fujita, 1999 [64], Sugita et al., 1999 [65], Sasakura et al., 2003 [66], Kikuchi & Tanai, 2005 [67], Toida et al., 2005 [68])

To provide a common specification that would apply to a wide water chemistry range, the more restrictive range for saline conditions is used to select effective clay dry density of about 1.4 Mg/m^3, which is in about the middle of the range. For this density, the required thickness of buffer to meet the design requirements is seen to be (Figure 4.4-10) about 450 mm for H12V and about 120 mm for the PEM.

[5] The buffer is assumed to be packed in the PEM container such that there is no significant gap between the buffer and the handling shell (see Section 4.4.1 (3) (v) (b)).

In addition to the above design requirements for buffer thickness, physical protection to assure the structural integrity of the overpack, has also to be considered during the period (> ≈ 1 ky) when its key safety function is ensuring complete containment (see Section 4.4.1 (2) (iii) (b)). As mentioned, in addition to buffer swelling pressure and hydrostatic head at repository depth, stability assessment considers additional loads from expansion of overpack corrosion products and bedrock creep (in the case of Neogene sediments). The details of the assessment are given in Supporting Report 4-16. Figure 4.4-12 (for 2 values of corrosion allowance (17 and 18 mm) for H12V in Table 4.4-4) shows the relationship between the buffer material thickness and the required pressure resistance thickness of the overpack lid.

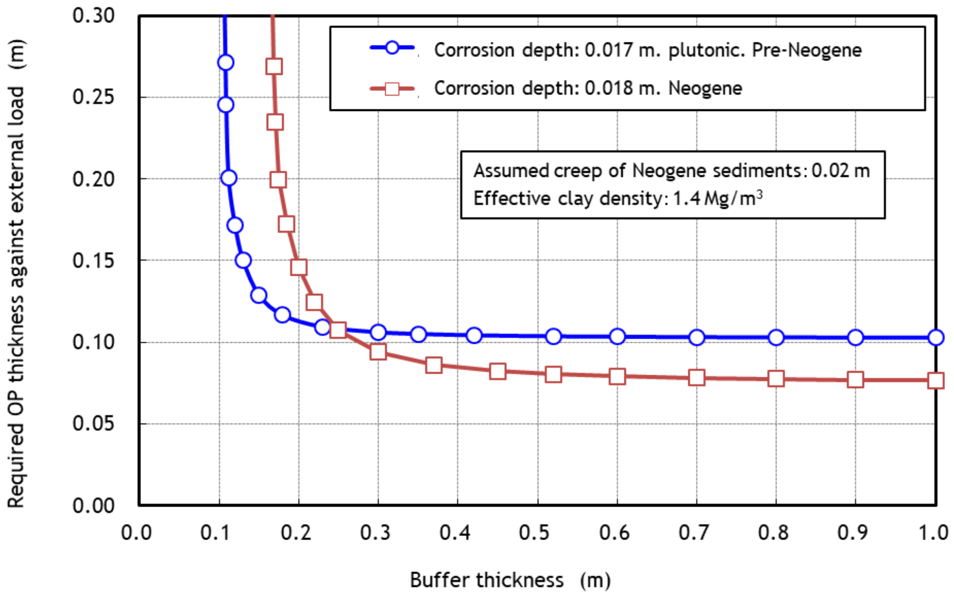


Figure 4.4-12 Relationship between the pressure-resistant thickness required for the overpack lid and the buffer thickness

From the viewpoint of safety, it is preferable to minimise the variation of the required mechanical stability thickness and hence this is taken to be 400 mm or more. From Figure 4.4-10, the minimum buffer thickness for H12V is about 450 mm, so this also covers this requirement. However, for the PEM the minimum thickness was 120 mm, so this was conservatively increased to 300 mm, bearing in mind the significantly lower corrosion in the PEM case (11 mm).

Based on these results, the reference specifications derived are presented in Table 4.4-8. As in H12, the buffer thickness was set at about 700 mm to have a sufficient safety margin over the required minimum thickness (450 mm for H12V, 300 mm for the PEM), bearing in mind uncertainties involved in quantifying long-term performance.

Table 4.4-8 Buffer material specifications (formulation and density) for HLW

	Formulation (Dry weight ratio)	Density	
		After saturated swelling (Set specification)	Production condition*3 (reference)
H12V	Bentonite 70% Sand 30%	Dry density*1 = 1.6 Mg/m³ Effective clay dry density *2 ≈ 1.4 Mg/m³	Dry density ≈ 1.8 Mg/m³ Effective clay dry density ≈ 1.6 Mg/m³
PEM			Dry density ≈ 1.7 Mg/m³ Effective clay dry density ≈ 1.5 Mg/m³

*1 Dry density: dry density of the mixture of bentonite and silica sand
*2 Effective clay dry density: dry density of bentonite excluding silica sand
*3 State at the time of production: before buffer material swells following infiltration of groundwater

However, as in the case of the overpack, there may be prospects for optimising this design. In the case of adopting the PEM option, the production constraint is less, since the impact of gaps is smaller compared to H12V blocks.

(iv) Evaluation of long-term buffer stability

Based on Table 4.4-7, the buffer specifications given above need to be evaluated to determine mechanical stability, both in terms of evolution of the EBS and impacts of major earthquakes. Details of the analyses are given in Supporting Report 4-17, while key results are presented below.

After repository closure, the density of the buffer changes as the overpack gradually corrodes, with expansion of overpack corrosion products, and as a result of bedrock creep (in the case of Neogene sediments). As buffer is deformed and shear stress increases, its continued ability to support the weight of the overpack has to be assessed, considering also consolidation (secondary consolidation) of the plastic buffer due to slow overpack sinking. Figure 4.4-13 shows the results of such an analysis.

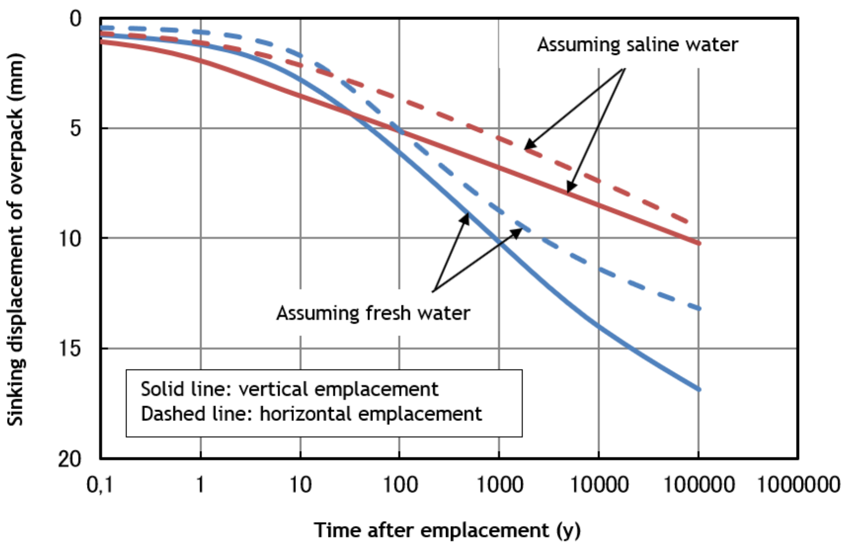


Figure 4.4-13 Overpack sinking over time

The amount of overpack settling is larger for freshwater conditions, as plasticity of buffer decreases with increasing salinity. In the case of H12V, sinking is about 11 mm after 1 ky and 17 mm after 100 ky, while for the PEM it would be about 6 and 9 mm, respectively, at these times. Even though sinking continues after 100 ky, the rate decreases with time due to secondary consolidation and hence the increase in sinking up to 1 My would only be in the order of several mm. Thus, the buffer material is believed to maintain the minimum necessary thickness over the assessment timescale with a good safety margin. Ca bentonite is less plastic and hence, even in freshwater, sinking would be less than the Na bentonite/saline water case [64], [67].

Figure 4.4-14 shows the stress ratio severity distribution for buffer in plutonic rock after corrosion product swelling is complete (very conservatively assumed to be ≈ 20 ky - obtained by corrosion product swelling analysis). The stress ratio severity is defined as normalising the effective stress ratio (q/p', where q is the deviator stress and p' is the mean effective stress) with the effective stress ratio at failure (the critical state parameter M) and it is an index showing how close conditions are to failure through shearing – see Supporting Report 4-17 for further details).

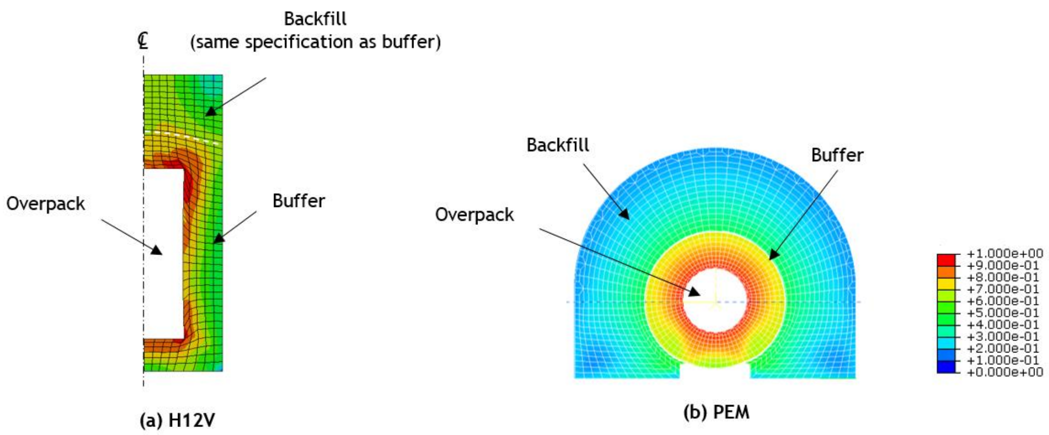


Figure 4.4-14 Distribution of stress ratio severity of buffer around overpack (plutonic rock, fresh water conditions)

The stress ratio takes values from 0 to 1, with risk of failure increasing as it gets closer to 1. For H12V, marginal regions are limited to overpack corners (actually rim, but looks like corners in the 2-D profile) while the PEM does not approach this critical state. In any case, there seems no risk of damage extending throughout the entire buffer thickness. From the analyses conducted, this conclusion applies also to other rock types.

To assess impacts in the event of large earthquakes, seismic response analysis of dynamic EBS stability was carried out. This was based on observations of ground motions from Japan's largest earthquakes, such as the 2011 Tohoku-Pacific Ocean earthquake, together with conservative conditions for the response analysis [46] [47]. This confirmed that, for all analysed cases, sufficient safety margins assure that stresses generated would not significantly damage either buffer material or the overpack.

In addition to ground motion from distant earthquakes, movement of existing faults needs to be considered. As mentioned in Chapter 3, areas containing large active faults are excluded during site selection. Furthermore, as shown in Supporting Report 3-35, the extent of displacement due to a single fault movement is related to its length, being about 80 cm for a fault length of 10 km, the size of largest faults assumed to be present at the repository site, but avoided during layout (see Section 4.1.3). Thus, displacements large enough to make the overpack contact the rock would not be expected to occur for a buffer thickness of 70 cm. However, even if the probability is very low, Section 6.4.3 (2) considers such rare event scenarios to assess if radiological impacts could be significant.

To improve understanding, modelling studies have been carried out for different positions of the moving fault. These indicate that, as long as the displaced overpack does not contact rock, a sufficient plasticity of the buffer will protect the overpack from serious damage [69] [70] [71] [72]. As shown in Figure 4.4-15, shear deformation by faulting causes the overpack to rotate in the buffer, with concomitant stress. In the case of the analyses shown in this figure, the von Mises stress produced on the inner surface of the overpack is at most 16 MPa, additional to the total buffer and the pore water pressure of 25 MPa, giving a total stress of 41 MPa [71]. Since this is only about 25% of the yield stress of the overpack (carbon steel SF340A), absence of failure can be assured with a sufficient safety margin.

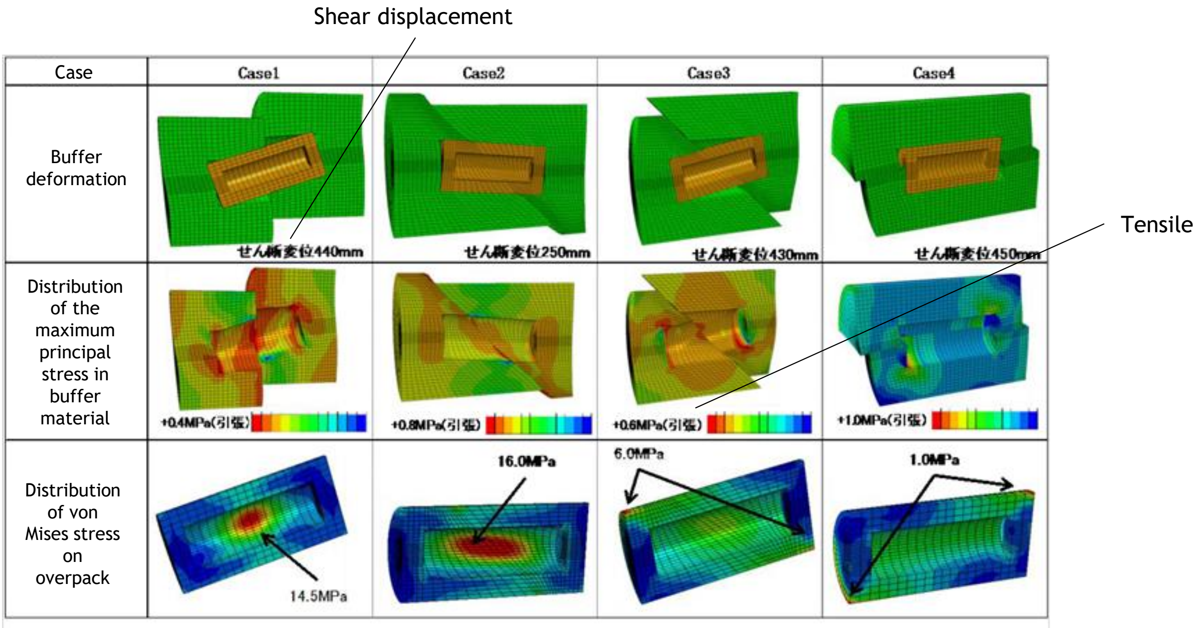


Figure 4.4-15 Shear stress sensitivity analysis of the HLW EBS (Source: JAEA, 2014 [71])

The models showed that the structural integrity of the overpack can be assured even for shear deformation up to 140% of the buffer material thickness (1 m) [70]. For the buffer itself, fractures may form due to the occurrence of shear bands along the shear surface, but self-healing of such fractures (as with those generated by gas breakthrough) and recovery of hydraulic barrier properties have been confirmed by experiments [73].

(v) Buffer production

(a) Compacted blocks

Figure 4.4-16 shows a buffer block 35 cm in height being manufactured by compaction with a 2000 t uniaxial press machine. It was verified that the dimensional change of the buffer block after removal from the mould (dimensions change gradually after the compaction force is released) can be controlled to some extent by varying the time, speed and holding time of compaction, based on the material conditions.

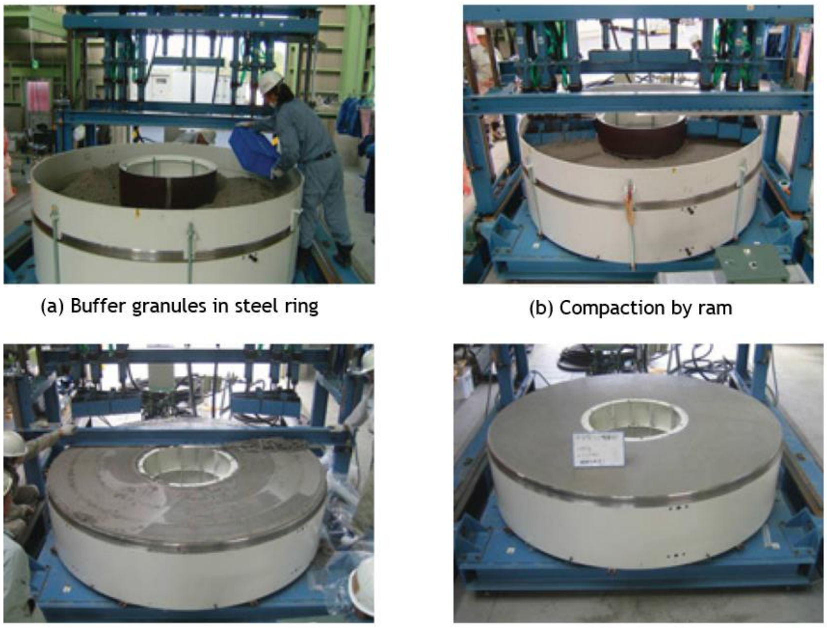
(a) 2,000 t press machine (b) Form removal (c) Finished bentonite block

Figure 4.4-16 Buffer block fabrication by uniaxial press (Sources: (a) [61]; (b), (c) [74])

It is known that cracks can occur in the buffer block during mould removal, so techniques should control such cracking. For a mixture of 70% bentonite and 30% silica sand with a 9% water content, the goal of a dry density of 1.9 Mg/m^3 was obtained in all test cases (10 cases) and it was confirmed that a high-quality block, with no defects such as cracks, could be produced [61]. In addition to the results from single-axis press machines, block manufacture by cold isostatic pressing (CIP) has also been confirmed [61] [75].

(b) PEM buffer

PEM buffer manufactured by compaction using a pneumatic ram is shown in Figure 4.4-17 [48]. In this method, buffer as powder is poured into a steel shell ring corresponding to a section of the PEM handling shell and compacted by the ram to produce ring-shaped buffer segments.



(a) Buffer granules in steel ring (b) Compaction by ram

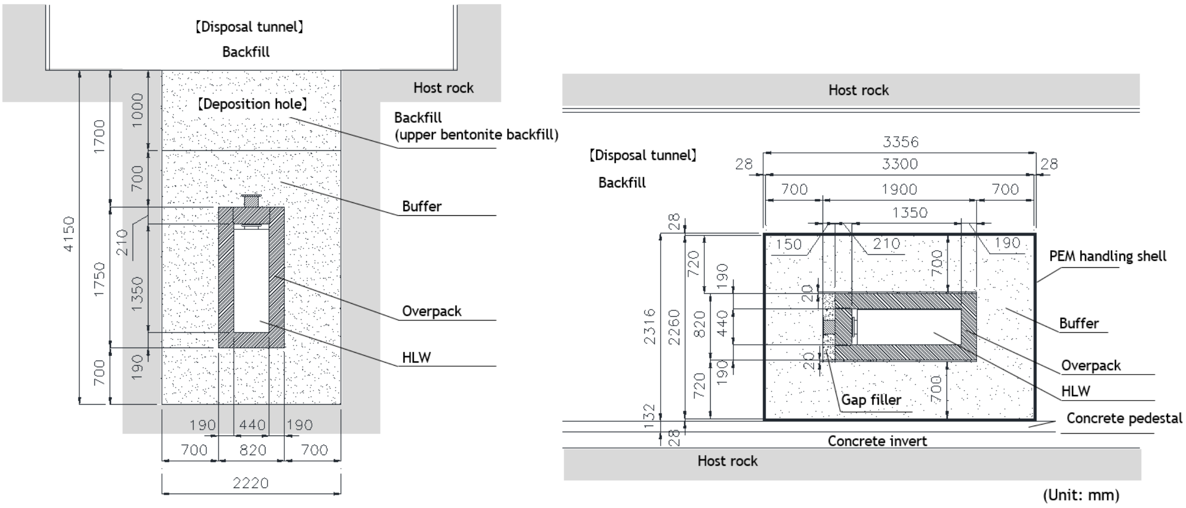
(c) Surface smoothing (d) Finished product

Figure 4.4-17 PEM buffer production ([48])

Compaction occurs in steps and, to date, a step size of ≈ 50 cm has been tested. Since buffer compaction could occur within the actual PEM shell, there would be no gap at the interface. Tests were conducted on material with 18% moisture content and a mix of 70% bentonite and 30% silica sand. In the test, the buffer dry density goal was 1.9 Mg/m^3, but the average value after fabrication was slightly lower (at 1.8 Mg/m^3), but still above the 1.7 Mg/m^3 specified in Table 4.4-8. Low density measured near the inner side of the ring was attributed to loss of the compacting pressure due to insufficient rigidity of the inner frame. Therefore, it was considered that this could be solved by increasing the rigidity of this component. Although demonstrating fundamental practicality, further R&D will focus on developing an optimised approach to PEM buffer production, in terms of both operational logistics and quality achieved.

(4) EBS specification

Sections 4.4.1 (2) and (3) provide specifications of the HLW overpack and buffer. Figure 4.4-18 brings these together (with specifications of disposal holes from Section 4.5.2 (2) (i)). For H12V, the surface dose rate of the overpack is 11 mSv/h (30 years interim storage; see Supporting Report 4-18). Therefore, in order to allow for the option of manual backfilling of the disposal tunnel after waste emplacement, backfill material with a thickness of 1 m is required on top of the buffer (from H12).



(a) H12V **b) PEM**

Figure 4.4-18 HLW EBS specifications

Details of the design and specifications of the PEM are given in Supporting Report 4-19. The PEM is assumed to be fabricated on the surface and then transported and emplaced underground. Accordingly, the handling shell must be able to withstand stress or impact forces during transport and emplacement without loss of structural integrity, requiring 28 mm thicknesses of carbon steel. In addition, the gap between the overpack and buffer is filled with bentonite pellets to prevent damage of the buffer due to vibration during transport. However, from the viewpoint of conservative specification to assure self-sealing (Section 4.4.1 (3) (iii)) 20 mm gaps were assumed unfilled. Due to additional shielding by the buffer and handling shell, the surface dose rate for the PEM is 3.1 μSv/h (after 30 years interim storage: see Supporting Report 4-18).

4.4.2 Design of the TRU EBS

(1) EBS objectives

TRU waste safety functions pre- and post-closure have been assigned to specific components of the EBS (Table 4.2-1, Table 4.2-5), as summarised in Figure 4.4-19. These provide input to design of waste packaging, infill between waste packages and buffer (when present). The TRU waste components and primary containers are specified in Section 4.2.2 (2). For disposal, these are conditioned within waste emplacement packages, as in the TRU-2 report and discussed further in Section 4.2.3 (2) (ii). Two types of waste package are assessed, waste package A designed for emplacement with a fork lift and a more robust type, waste package B intended to be emplaced by a gantry crane [76]. Alternative waste package designs (e.g. with greater longevity for Gr.2 wastes) are being considered but development is at an early stage and hence only the well-studied packages A and B are assessed in this report.

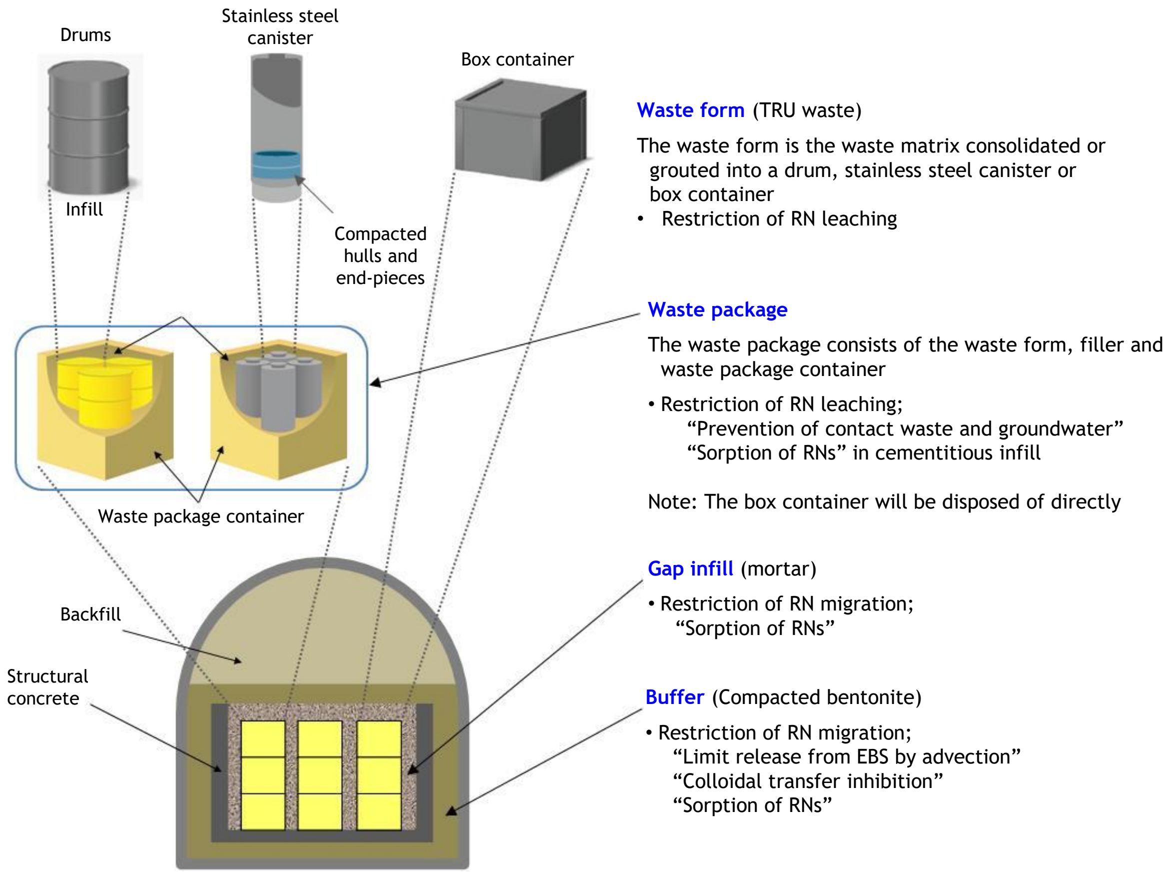


Figure 4.4-19 TRU EBS components and safety features

(2) Design of TRU waste package

TRU waste is classified into 4 groups and conditioned in drums, canisters or box containers as indicated in Table 2.1-2. This waste has a low thermal output compared to HLW, allowing transport and emplacement of multiple containers to improve operational efficiency. The TRU-2 report illustrated emplacement packages, each containing four 200 litre drums, four canisters or two BNGS 500 litre drums (now no longer being considered for disposal), with voids filled with mortar. These emplacement packages, together with the box containers, can be readily stacked in disposal vaults. In the following, after showing the design requirements and evaluation items of the waste package, design examples of each component are shown.

(i) Waste package design requirements

The design requirements of the emplacement waste packages are shown in Table 4.4-9. Operational safety requirements (safety functions) focus on preventing leakage of RNs during all operations (Table 4.2-1). Corrosion resistance and structural integrity are set as design requirements to ensure these safety functions. In addition, practicality of fabrication and the ability to emplace the package by remote handling are set as implementation design requirements. The key post-closure safety requirement (safety function) is restriction of releases of RNs (Table 4.2-5).

Table 4.4-9 Waste Package Design Requirements

Design requirements	Objective	Specifications
Corrosion resistance	The function of preventing leakage of RNs during operation is not impaired by corrosion	Container material thickness
Structural integrity	During operation, the function of preventing leakage of RNs is not impaired by applied loads	Container material thickness, waste package infill, handling features
Production practicality	Package can be manufactured by existing technology or technology which will be realised in the near future	Container material, shape
Remote waste packaging	Waste can be placed in a package, which is infilled and a lid added by existing remote handling technology or technology which will be realised in the near future	Container material, internal dimensions, waste package infill, lid, lifting features
Remote package emplacement	Waste packages can be emplaced in disposal vaults by existing remote handling technology or technology which will be realised in the near future	Shape, lifting features

After the closure of the disposal vault, groundwater will infiltrate and gradually saturate buffer, backfill and other porous materials, while the higher thermal output of waste Grs.2 and 4H will decrease as short half-life radionuclides decay. This transient period is considered to be up to around 300 years, based on previous studies [77]. As discussed in Section 6.3, quantification of RN release (identified in Table 4.2-5) for evolving conditions of temperature and saturation during this transient is associated with great uncertainties. Therefore, complete containment is particularly valuable for the first 300 years. This is captured in Table 4.4-10, along with a breakdown of the objective in terms of design requirements.

Table 4.4-10 waste package evaluation items

Evaluation item	Objective
Complete containment	Have corrosion resistance and structural integrity for a specified period of time after closure

The details of the above design requirements and setting resultant evaluation items are provided in Supporting Report 4-20.

(ii) Design of waste package containers

(a) Container for waste package A

The TRU-2 report reference emplacement packaging design (now termed waste package A) included a steel shell (rectangular cuboid) of thickness 5 mm, infilled with cementitious mortar without a lid (used for all primary waste containers, except for the box containers).

Although here the containment function is unrelated to corrosion resistance, the primary waste is enclosed and hence the Table 4.2-1 safety function of preventing leakage of RNs during operations would be provided.

With respect to minimising loading that threatens structural integrity, the TRU-2 report and NUMO [1] have illustrated remote-handled emplacement with a forklift, which is facilitated by the gaps at the bottom of the waste package container (Figure 4.4-20).

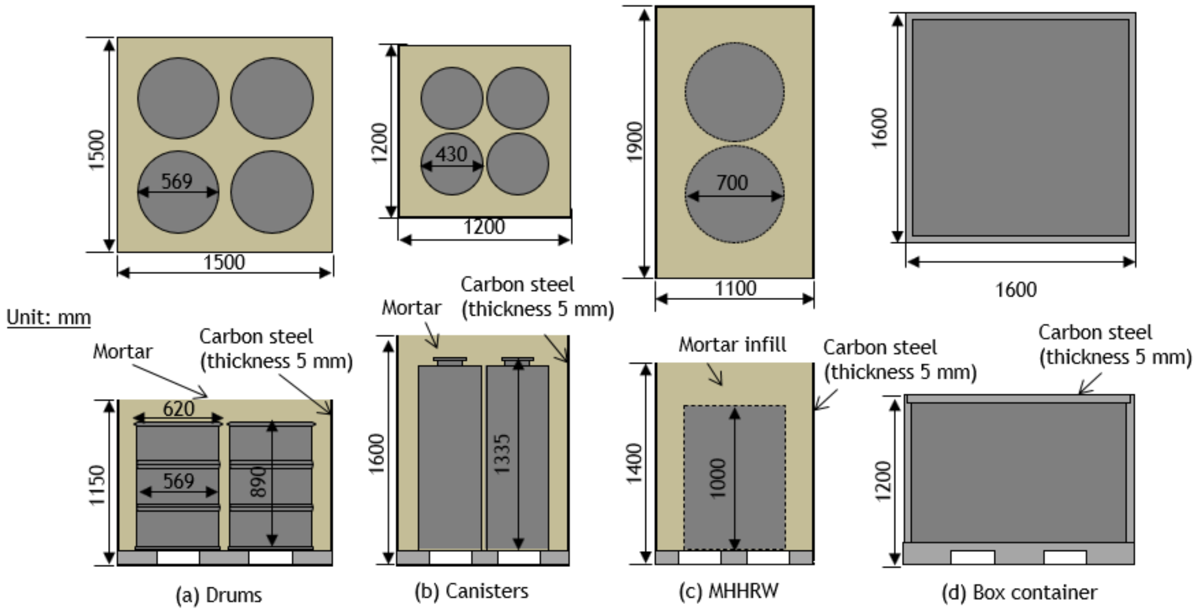


Figure 4.4-20 Waste package A specifications (the container for MHHRW (miscellaneous higher heat reprocessing waste) has yet to be specified)

With regard to the load during stacking, the structural integrity is ensured by the strength of the infill in the waste package as described later, not the waste package container [10].

(b) Container for waste package B

The waste package B container (Figure 4.4-21) was designed for lifting by a crane for emplacement in the disposal vault. In the design, the shape of the waste package container is similar to that designed for medium-depth disposal (Rokkasho L1), which also assumes emplacement using a crane [21] [78].

Specifically, for SM400A/JIS G 3106 structural quality steel, the required corrosion resistance and strength for lifting and stacking can be provided by a container thickness of 50 mm and appropriate lifting structures. To reduce the risk of releases in the event of drops, the upper lid is sealed by welding. Studies of drops in Section 5.4.2 (1) (ii) show that such a container will maintain its integrity even for drops from the maximum lift height of 8 m.

Corrosion during the operational period, assuming exposure to air for a maximum about 8 years from waste packaging until vault infilling, would result in an average corrosion depth is 0.5 mm, which would have little impact on the total wall thickness of 50 mm. Further details of waste package B design and structural integrity studies are provided in Supporting Reports 4-21 and 4-22.

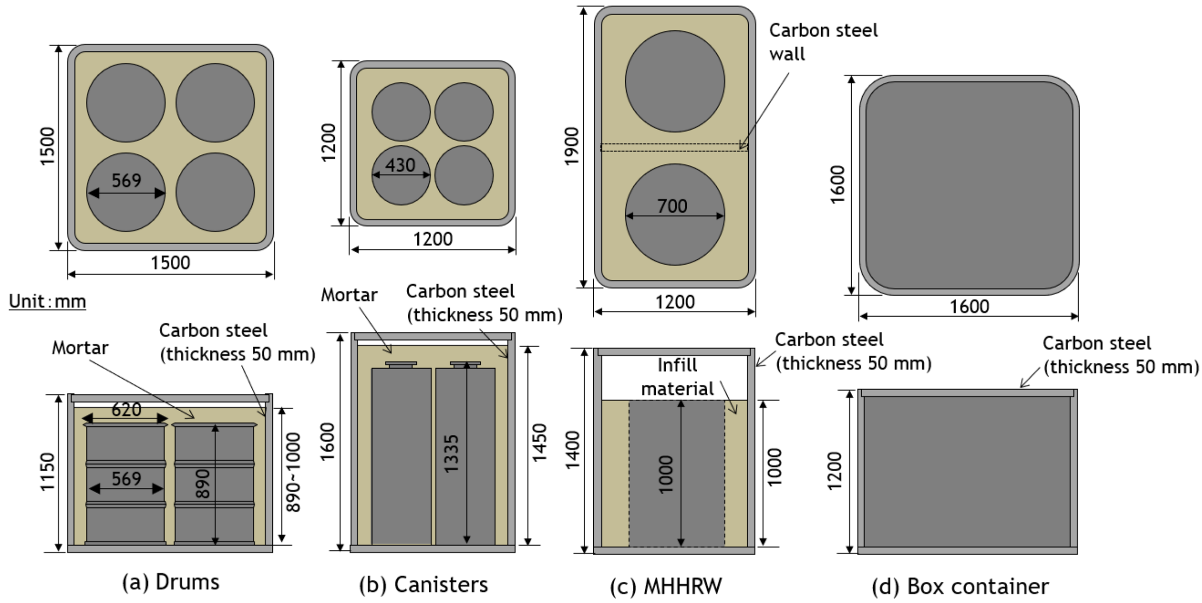


Figure 4.4-21 Waste package B specifications (the container for (c) has yet to be specified)

Grs.2 and 4H have higher radioactivity and could generate hydrogen gas by radiolysis of water contained in the mortar infill. In the case of waste package A, generated hydrogen gas would pass through the mortar infill without a significant pressure build-up. For waste package B, which is sealed by welding, the carbon steel container should be able to withstand any pressure from hydrogen gas build-up. To evaluate the pressure tightness, the internal pressure from hydrogen gas build-up in this waste package was calculated from the amount of gas generated by radiolysis of water in the mortar infill between waste drums or canisters, mortar infill or concrete matrix within the waste packages for all groups. If dry sand is used instead of the mortar-infill in the packages, the pressure from hydrogen gas may be reduced. This alternative infill material was also considered for Grs.2 and 4H.

Hydrogen gas build-up within the waste packages for Grs.1, 2, 3 and 4L calculated until repository closure, was within that considered acceptable to ensure the structural integrity of the waste packages (i.e., within the pressure threshold). In the case of Gr.4H, the application of an alternative design using dry sand and a high strength steel (e.g., JIS G3115 steel plate SPV490 for pressure vessels) was more effective in ensuring the structural integrity. In this case, a separation steel wall should be included in order to prevent heterogeneous distribution of dry sand in case of inclination during operation (see Figure 4.4-21 c). Details of hydrogen gas production and associated evaluation are described further in Supporting Report 4-22.

The above evaluation can be updated if, at any point in the future, the properties of the generated waste change. It may be worth mentioning that reducing hydrogen gas generation will also reduce the risk of rupturing the waste package container. A reduction of moisture content in the mortar, or utilisation of dry sand instead for the infill, would be effective in this regard and may be considered further in the future.

(iii) Design of waste package infill

Remote-handled waste package infill using a tailored mortar (for example, in terms of fluidity, setting characteristics) is described in the TRU-2 report and [11].

For structural integrity during stacking, an infill strength of 30 MPa is required [79]. This and other required characteristics can be obtained with the formulation shown in Table 4.4-11, which does not include minor components introduced to facilitate production.

Table 4.4-11 Waste package infill formulation [79]

Mortar (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)
483	266	1,449

In the case of waste package B, the steel container has a thickness of 50 mm and is designed to withstand loads during stacking. For this reason, it is not necessary to ensure the structural support of the mortar infill against the stacked load. For groundwater pressure loads on the container after repository closure, the mortar infill may act as mechanical support. However, in the case where dry sand is used as an infill for Gr.4H (see Section 4.4.2 (2) (ii) (b)), structural integrity should be ensured by the waste package container alone.

The mortar infill may reduce groundwater penetration and hence slow down RN leaching and, additionally, may retard RN migration by sorption [11]. Cracks that form due to mortar shrinkage may affect RN migration and will be discussed further in Chapter 6.

Initially, the calculation the impact of gas was not considered. Subsequent calculations suggest that the impact of gas generation due to corrosion is negligible, but this is still an open issue, as discussed further in Chapter 6.

(iv) Waste package specifications

From the above, waste packages A and B, for each type of primary waste container, are given in Table 4.4-12 (illustrated in Figures 4.4-20 and 4.4-21, respectively). The external dimensions of waste packages A and B for specific primary containers are effectively the same and maximum thermal output and weight of these are provided in Supporting Report 4-21.

Table 4.4-12 Specifications of waste packages A and B

Waste Gr.	Primary waste container	Primary containers per package	Waste package infill		Material for waste package container (JIS)	
			Waste package A	Waste package B	Waste package A	Waste package B
1	Drum	4	Mortar	Mortar	SM400A	SM400A
2	Canister	4	Mortar	Mortar	SM400A	SM400A
3	Drum	4	Mortar	Mortar	SM400A	SM400A
4L	Drum	4	Mortar	Mortar	SM400A	SM400A
	Box container	1	-	-	SM400A	SM400A
4H	Drum	4	Mortar	Mortar or dry sand	SM400A	SPV490
	MHHRW*	2	Mortar	Dry sand	SM400A	SPV490
	MHHRW	2	Mortar	Mortar	SM400A	SPV490

* Miscellaneous higher heat reprocessing waste

In the case of the waste package A, RNs can be contained by mortar infill, while the RN containment during operation is improved in the case of waste package B due to the welded lid. In addition, waste package B may also improve post-closure containment, even if this is not rigorously quantified. The corrosion resistance and mechanical integrity of waste package B during the post-closure phase are discussed further below.

(v) Evaluation of corrosion and structural integrity after closure

(a) Waste package A

In the case of waste package A, first contact by infiltrating water occurs after surrounding buffer and backfill have saturated and water then penetrates the structural concrete and inter-package filling. Even then, water must saturate the mortar and the primary waste container must fail before releases of RNs from the waste will occur. It is reasonable to expect that this will take an extended period of time, but is very difficult to quantify. Thus, although some scoping calculations indicate this might take about the target 300 years [77], there is great uncertainty in this – leading to the very conservative assumption made in safety assessments that RN release starts soon after recovery from the initial transient, as described later in Chapter 6.

(b) Waste package B

Although the initial conditions for waste package B are similar to those described above for waste package A, as package B is thick-walled with a welded lid, it can be assured that no RNs are released until the package fails.

Because it is surrounded by mortar, the ambient pH is high and it is expected that corrosion would be even lower than that considered in Section 4.4.1 (2) for the HLW overpack design. Under highly alkaline conditions, the average corrosion rate of carbon steel in the initially oxidising environment would be $< \approx 1$ μm/y [80], while, in a reducing environment, $< \approx 0.1$ μm/y has been reported [81]. Since it is difficult to estimate the time for transition from oxidising to reducing conditions within the disposal vault, the average corrosion depth for 300 years was determined conservatively, using a corrosion rate of 1 μm/y. The average corrosion depth would thus be 0.3 mm, which, taking account of non-uniform corrosion [82], would give a maximum corrosion depth of 5.3 mm, indicating penetration of the 50 mm thick wall would not occur.

Incidentally, the corrosion of carbon steel in an alkaline environment is not accelerated at radiation doses up to at least 25 Gy/h [83], so the maximum surface dose of about 1 Gy/h for wall thickness of 50 mm [11] indicates that this is not a concern. Further details of this evaluation are provided in Supporting Report 4-23.

An average corrosion rate of 0.3 mm over 300 years is not expected to significantly impact the structural integrity and hence mechanical analysis was carried out assuming the full wall thickness of 50 mm. The stress applied to the waste package container walls was calculated based on external and internal forces. The external force applied to the container, in the case of plutonic rocks and Pre-Neogene sediments for a repository at 1,000 m depth, includes a hydrostatic pressure of 10 MPa (maximum case). The internal pressure caused due to radiolytic hydrogen gas within a 300 y period was also considered. As a result, the stress applied to container walls was highest in the case of Gr.1 (no significant radiolysis) at 10 MPa.

From an elasto-plastic analysis, distortion of the side plate and bottom plate of the waste package in contact with the solid mortar was shown to be extremely small. The top plate was plastically deformed due to the 50 mm gap at the top of the container, but the amount of distortion did not reach the critical strain. From these results, it is considered that the waste package container does not fail in this case. If required, it is possible to suppress deformation by measures such as reinforcing the top plate and increasing the thickness of the waste package container.

It is therefore assumed in the post-closure safety assessment for waste package B that RN release starts at least 300 years after closure. More realistically, demonstration of greater longevity may be possible – potentially on timescales in the order of thousands of years. For this, more detailed evaluation of structural integrity as the corrosion depth increases would be needed. It should also be noted that stress-corrosion cracking at areas where residual welding stress occurs was ignored in the evaluation and hence R&D to reduce the risk of SCC may be needed for this package. More information on this evaluation of the structural integrity is included in Supporting Report 4-24.

(vi) Production of the waste package container

The waste package container can be manufactured by bending steel plates, as considered in this report, or by casting. These methods of fabrication have been confirmed by full-scale demonstrations associated with the L1 interim depth repository project [76] [84] (e.g. Figure 4.4-22) and hence required technology is assumed to be available.

(a) Prototype waste container (b) Welding demonstration

Figure 4.4-22 Fabrication tests of the waste material container ([76])

(3) Design of infill for the disposal vault

(i) Design requirements for gap infill

The design requirements for vault infill are shown in Table 4.4-13. An operational safety requirement is to provide radiation shielding for any case when workers are present (see Table 4.2-1). The infill complements self-shielding by the waste packages themselves, reducing doses to any workers present, particularly at the time of construction of the buffer/backfilling barriers above the emplaced waste.

Table 4.4-13 Gap infill design requirements

Design requirements	Objectives	Specifications
Shielding	Reduces dose to workers, if present for backfilling work	Thickness of gap infill around waste packages
Remote-operated emplacement	Have sufficient fluidity for gap filling between waste packages Resistance to separation during pumping	Ingredient mix, infilling plan
	Separation of waste packages from each other and walls during emplacement	Gap infill thickness

Sorption of RNs was set as a post-closure safety requirement (safety function), (Table 4.2-5), although infill may contribute also to restricting RN solubilities. As noted in Section 4.2.4 (2) (ii), there is no need to consider the thermal alteration of cement minerals for waste Grs.1, 3 and 4L when assessing this requirement, although this is a factor for the groups with higher heat output.

In order for the safety function to be assured, mortar must be emplaced in a quality assured manner that fills all void space and thus this is a consideration for remote emplacement, which is set as a design requirement to assure practicality.

(ii) Infill material

The composition of the mortar infill must satisfy the above design requirements. As described in TRU-2 and NUMO (2011) [11], mortar was chosen as an infill material that could be easily emplaced by remote-handling, avoiding radiation exposure from TRU waste.

Reduction of RN release by the mortar in the post-closure phase is also required (See Table 4.2-5), while mechanical strength should be sufficient to assure stability of stacked A waste packages. RN release reduction is provided by the low permeability and sorption capacity of mortar, compared to an unfilled case. An example of composition of mortar infill which meets the mechanical strength criteria of 30 MPa has been reported [79] and is given in Table 4.4-11. Workability with remote-handling was also checked for this mortar [79]. Fracture formation in mortar infill is likely but, if the water flow rate is sufficiently low, RN migration may be limited, as discussed further in Chapter 6.

For waste package B, RN release is constrained by both the metallic container and the mortar infill. The mechanical strength for stacking is provided by the container walls rather than the mortar infill, due to the void space that remains in the infilled package.

(iii) Thickness of infill between waste packages

Waste package clearances, between stacks and from the structural framework walls, are conservatively taken as 150 mm based on an assessment of swinging of waste packages during emplacement using a gantry crane. The same clearance is also assumed for emplacement using a forklift. There is certainly potential to reduce these values as equipment designs are developed.

It is assumed that, after infilling, workers could be present to emplace the overlying buffer/backfill. Buffer emplacement at the side of the structural framework is assumed to occur prior to commencement of waste package disposal (Section 4.4.3 (2)). However, if there is a problem with the side buffer, manual removal and replacement is assumed.

For radiation shielding design, the effective dose limit for workers under normal conditions (50 mSv over 1 year, 100 mSv over 5 years) is used to calculate the infill thickness needed to provide the required shielding. For backfilling the top of the vault, a 48 hour working week is assumed (equivalent to10 μSv/h), but only 10 hours per week working at the side (50 μSv/h). Table 4.4-14 shows very conservative estimates of the required infill shielding thickness (assessment described in detail in Supporting Report 4-25). This distinguishes between waste packages A and B due to the different container wall thicknesses (5 mm and 50 mm, respectively), with the latter providing more self-shielding. Incidentally, Gr.1 requires no shielding but an infill thickness of 100 mm at the top is assumed for physical protection and 150 mm at the side due to emplacement considerations, as mentioned above.

Table 4.4-14 Gap infill thickness

Waste Group	Top (mm)			Side (mm)		
	Required shielding thickness		Set value*	Required shielding thickness		Set value
	Package A	Package B		Package A	Package B	
1	0	0	100	0	0	150
2	980	860	1,200	220	110	300
3	510	550	600	0	0	150
4L (Drum)	900	940	1,050	250	140	300
4L (Box container)	440	430	450	0	0	150
4H (Drum)	700	740	800	80	0	150
4H (MHHRW)	780	960	1,000	220	120	850

* Although set values are all conservative, the safety margin is quite variable as thickness is also constrained by vault geometry as discussed later.

(4) Design of buffer

(i) Design requirements and evaluation items for the buffer

The TRU waste EBS includes a buffer for Grs.1, 2 and 4H, which have higher thermal output and/or contain relatively high contents of poorly sorbing nuclides. As noted in Section 4.2.4 (2) (ii), buffer placed around the structural framework (Figure 4.4-19) has the function of restricting RN transport. Design requirements and evaluation items, assuming use of bentonite-based buffer, are shown in Tables 4.4-15 and 4.4-16. In the future, based on feedback from post-closure safety assessment, the pros and cons of an external buffer will be re-evaluated for all waste groups.

Table 4.4-15 Requirements for TRU waste buffer design

Design requirements	Contents	Specifications
Low permeability	Restricting groundwater advection in the buffer, reducing transport of RNs	Material, effective clay dry density, thickness
Colloidal filtration capacity	Preventing RN migration in a colloidal phase	Material, effective clay dry density
Self-healing	Ability to close any openings generated after emplacement, e.g. due to gas breakthrough	Material, effective clay dry density
Manufacturability and engineering practicality	Ability to manufacture and install to required quality levels based on existing technologies or those which will be realised in the near future	Material, effective clay dry density, emplacement plan

Table 4.4-16 TRU buffer evaluation items

Evaluation item	Objectives
Mechanical stability during evolution of the EBS	Demonstration that long-term evolution of stresses due to the weight of the concrete emplacement structure and creep of rock does not significantly degrade the required functions of the buffer
Mechanical stability in the event of earthquakes	Demonstration that overpack and buffer do not lose mechanical stability in the event of large-scale earthquake motions

Note that there is no requirement for self-sealing of gaps as, based on full-scale tests, the buffer construction process for TRU waste is not expected to result in such gaps [85]. TRU waste buffer evaluation items and design requirements are discussed further in Supporting Report 4-26.

(ii) Choice of buffer material

Compressed bentonite is selected as a material that can satisfy the various buffer requirements. As for HLW, Kunigel V1 mixed with silica sand is selected as the buffer material to set the reference specification, with caveats as for the HLW case. As mentioned in Section 4.4.1 (3) (ii), bentonite permeability and swelling pressure is influenced by groundwater salinity, which varies as shown in Table 4.2-8. Potential alteration of Na-type bentonite by exchange with Ca is also considered.

(iii) Setting buffer density and thickness

Table 4.4-17 summarises the ranges of buffer effective clay dry density that meet the basic design requirements for low permeability, colloid filtration and self-healing for both fresh and saline water (conservatively considering seawater) and also alteration to Ca-bentonite.

Table 4.4-17 Effective clay dry density requirements for TRU waste buffer

Design requirements	Effective clay dry density (Mg/m^3)		
	Freshwater conditions	Saline conditions	Ca type
Low permeability	$> \approx 0.4$	$> \approx 1.1$	$> \approx 1.1$
Colloidal filtration capacity	$> \approx 0.8$	$> \approx 0.8$	$> \approx 0.8$
Self-healing	$> \approx 0.6$	$> \approx 1.2$	$> \approx 1.2$
Manufacturability and engineering practicality	$< \approx 1.6$ (field compaction)		

The details for setting these limits are given in Supporting Report 4-27. In general, lower density limits can be set for fresh water conditions, with higher limits being the same for both saline conditions and Ca-bentonite. All requirements can be met with effective clay dry density of 1.2 Mg/m^3, while the upper limit in terms of practicality of fabrication is 1.6 Mg/m^3. Buffer thickness in the TRU-2 report was related to the RN release rate [10], with 1.0 m selected to provide a suitable performance margin. Additional studies on the thickness and buffer density considering practicality and other safety functions will be carried out in the future.

Average effective clay dry density is specified to be 1.4 Mg/m^3 on the basis of sufficient performance margins as well as other considerations. Bentonite is assumed blended with silica sand at a mixing ratio of 30% to improve compaction performance. The dry density of 1.6 Mg/m^3 thus gives the target effective clay dry density of 1.4 Mg/m^3.

(iv) Evaluation of long-term buffer stability

After closure, the mechanical conditions in the EBS will slowly evolve as infiltrating groundwater saturates all porous media; metals (especially waste packages and structural rebars) corrode and swell; with also rock creep for the relatively low strength Neogene sediments. Leaching of structural concrete will result in reduced strength, while interaction of such leachate with buffer will cause its alteration. As for the HLW case, it is thus necessary to evaluate the long-term stability of the buffer in terms of both gradual evolution of the EBS and also ground motion resulting from earthquakes. The details of these evaluations are given in Supporting Report 4-28.

Figure 4.4-23 shows examples of the results after 100 ky of EBS evolution in terms of resultant buffer dry density distribution for TRU waste Gr.2 in plutonic rock (EBS specifications in Figure 4.4-25) and Neogene sediment. Geological data are taken from Table 4.2-6 and water chemistry from Table 4.2-8. In this simulation, the evolution of buffer mechanical properties due to Ca exchange and smectite dissolution is considered in addition to the evolving stress field resulting from loading by the structural concrete framework and swelling of metal corrosion products [86]. In addition, for Neogene sediments, bedrock creep is taken into account.

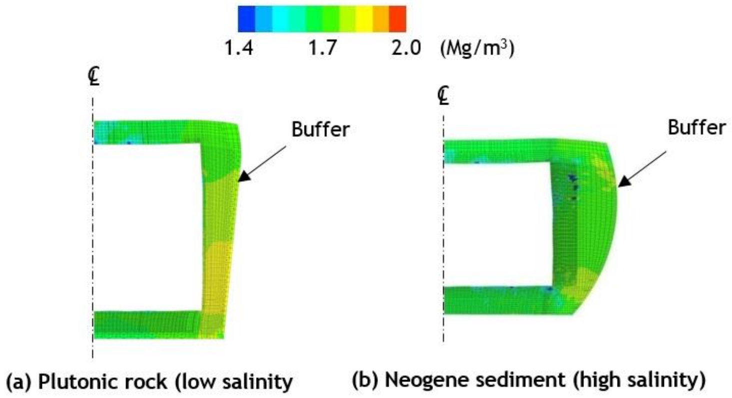


Figure 4.4-23 Buffer dry density distribution (after 100 ky)

The buffer is compressed by expansion of inner EBS components and, for Neogene sediments, external rock creep. Dry density of the buffer decreases only in very restricted areas of tensile stress, with no significant volume below the minimum specified value of 1.4 Mg/m^3 (effective clay dry density 1.2 Mg/m^3). Thus, it is considered that the buffer material can maintain the density necessary for assuring performance over a long period of time. From the viewpoint of supporting the load of the filled emplacement cell, the stress ratio severity of the buffer was noted to approach 1 – with a risk of failure – only in restricted areas, hence loss of performance of the entire buffer thickness is not expected.

An example of the results of the assessment of the impacts of earthquake ground motion is shown in Figure 4.4-24, again showing that the stress ratio severity of the buffer limit of 1 is reached in a few areas but does not penetrate the entire buffer thickness.

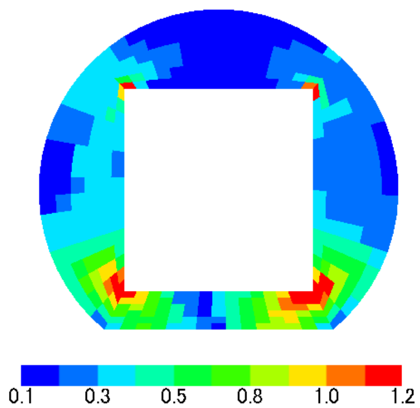
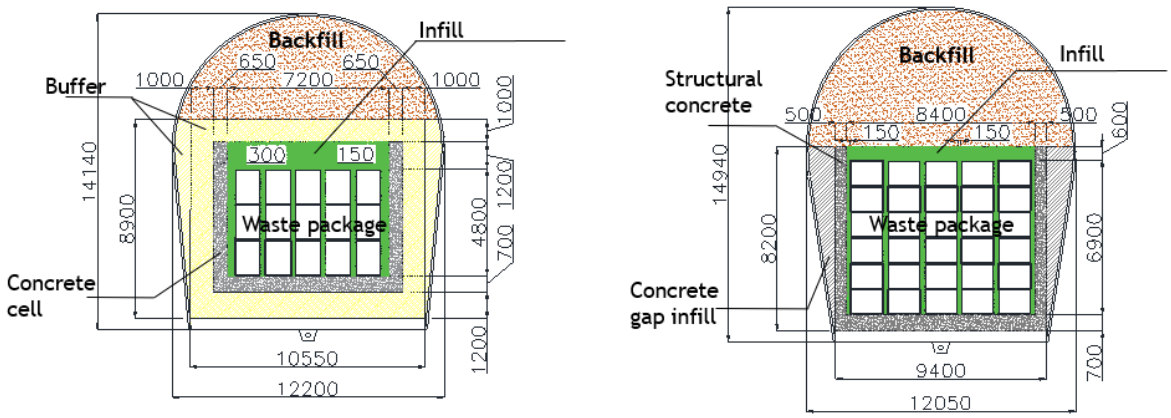


Figure 4.4-24 Maximum stress ratio severity in buffer as a result of earthquake motion

Taken together these results indicate that the TRU buffer can be assured to perform over assessment periods of > ≈ 100 ky.

(5) Specification of the EBS

Based on the above, TRU waste EBS specifications are derived for all rocks and cases with and without buffer. Examples are shown in Figure 4.4-25 (based on specification of the disposal vault developed in Section 4.5.2 (2) (i) (c)).



(a) With buffer (Gr.2) **b) Without buffer (Gr.3)**

Figure 4.4-25 EBS specification for TRU waste (for plutonic and Pre-Neogene sediments)

The buffer thickness required is 1.0 m, but at the bottom is set as 1.2 m to allow a sufficient margin for consolidation settlement. In addition, since the side gap between the vault liner and the concrete cell wall is filled with buffer, its thickness is > ≈ 1.0 m, depending on the shape of the vault.

4.4.3 Construction of the EBS and waste emplacement

Currently, construction and waste emplacement technology is still under development. The specifications given in this section are thus only illustrative examples, other options are being assessed and decisions on preferred technology would be made only when designs of the EBS become more advanced. Nevertheless, such basic concepts allow preliminary assessment of fundamental engineering practicality.

(1) HLW

(i) H12V

As described in Section 4.2.4 (1) (i), the overpack containing vitrified HLW is loaded on a dedicated transport vehicle at the surface facility and transported underground via an access ramp [1]. In case of manual operation, the transfer vehicle is provided with radiation shielding. Alternatively, if an access shaft is utilised, waste will be transported by a dedicated elevator capable of handling appropriate weights. The reference concept for transport of waste to the repository is by ramp, using either a road-based transport vehicle such as a truck or a rail-based transport vehicle. To allow the ramp access route to be used for other purposes and from the viewpoint of transport flexibility, a road-based transport vehicle is selected as the reference [1] (although alternatives may be considered in the future).

After removal from the ramp transporter at a temporary storage location (see Section 4.5.4 (4) (iii)), the overpack is transported through the connecting tunnels to the disposal tunnel, in which it is emplaced in a hole already containing buffer (as shown in Figure 4.2-2 (a)). For a prepared emplacement hole, lower buffer cylindrical blocks and surrounding rings are lowered into place (using a vacuum gripping device) before the overpack is inserted and upper buffer blocks added to fill the hole (Figure 4.4-26).

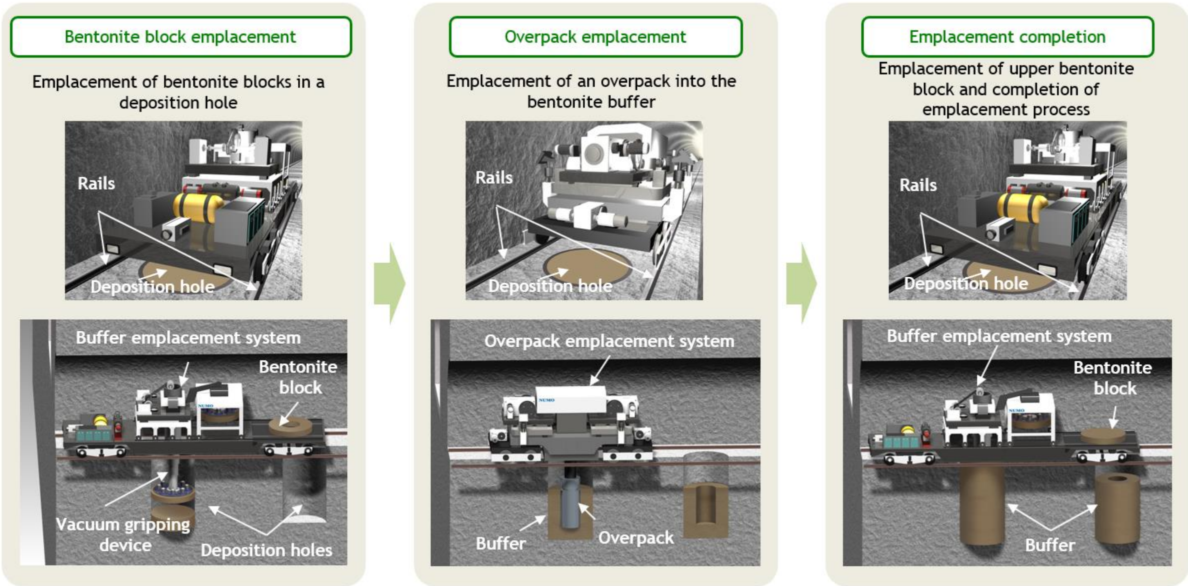


Figure 4.4-26 Buffer and waste emplacement procedure (H12V). These procedures were developed assuming low water inflow rate into the holes

As noted in Section 4.4.1 (4), the surface dose rate of the overpack is ≈ 11 mSv/h, so emplacement would involve remote-handling technology. Further studies will be required for the installation sequence of overpacks (to ensure hole stability) and will probably also require to be adapted to site conditions and the final selection of buffer composition.

Emplacement equipment for the overpack and buffer using rail transport has been demonstrated at full-scale [87] [88]. A vacuum lifting technique is being developed for bentonite blocks that is effective in the limited space available and allows loading, unloading, transfer and emplacement of buffer blocks without damage. This has been shown to fail-safe (designed so that any credible accident does not lead to a significant perturbation) even in the event of failure of the vacuum pump, based on full scale tests [87] [88] [89]. To allow accurate block emplacement in disposal holes, the vacuum grip is incorporated into a telescopic arm for lowering into place. Supporting Report 4-29 overviews demonstration tests of buffer block fabrication and emplacement technology.

Since the buffer material starts swelling immediately when it comes in contact with high humidity air or water, the inner surface of the buffer material may deform, preventing emplacement of the overpack. Thus, buffer must be kept dry until the overpack emplacement is completed, as described in the following.

To avoid buffer wetting, a method involving a protective rubber sheet has been studied [90]. This rubber sheet is assumed to be removed after successful emplacement of bentonite buffer blocks, but this has not yet been examined to check practicality. Thereafter, inflowing water into the hole contacts the bentonite buffer blocks, which start to swell. After saturation, the desired properties of low permeability and colloidal filtration will be obtained. However, it should be noted here that more studies will be needed to confirm whether such a method would be practical or if other means of buffer protection would be needed.

If the water inflow rate is sufficiently large, there is a risk of piping-erosion (see 4.5.4 (5)), which may lead to deterioration of performance. Either such holes would be rejected or a technique used to reduce water inflow (e.g. by grouting or use of a hole liner). If water inflow control measures were to be used, the post-closure safety implications would need to be assessed while, if some disposal holes are not useable, their likely number needs to be estimated in order to allow for this, as described in Section 4.5.4 (5).

The above procedures require remote handling to reduce radiation exposure to workers. Techniques related to accurate positioning and autonomous control thus become important, but, in recent years, such an approach is well supported by advances in relevant technology [91].

(ii) PEM

The PEM is assembled on the surface and transported underground, as for the H12V overpack. The PEM is 3.4 m in length and 2.3 m in diameter, and has a weight of ≈ 37 Mg (specifications given in Figure 4.4-18 and more details in Supporting Report 4-19). The surface radiation is reduced by self-shielding to ≈ 1μSv/h. Within the underground facilities (see Section 4.5.4 (4) (iii)), the PEM is transported through the connecting tunnels to the disposal tunnel, in which it is emplaced by remote-handling technology (as shown in Figure 4.2-2 (b)).

The PEM is large and heavy, so special equipment is required for its transport and emplacement, and also for filling the gap between the PEM and the disposal tunnel; this is currently under development. One approach to PEM emplacement within a small tunnel utilises an air caster system, which has been demonstrated in full-scale tests [92]. In particular, SKB has demonstrated a form of PEM transport and emplacement (KBS-3H) at full scale in the Äspö underground laboratory [14].

Although the air caster system reduces the gap between the PEM and the tunnel wall allowing reduction of the diameter of the tunnel, the contact surface is required to be smooth and needs a special device for filling remaining gaps, requiring complex operations after each PEM is emplaced. To avoid such problems, a larger diameter tunnel is considered in this report, together with PEM transportation/emplacement by a mobile lifting unit [1]. More details on PEM fabrication, transport and emplacement are given in Supporting Report 4-30.

The effect of high humidity or groundwater in the disposal tunnel is much less for PEM emplacement compared to H12V. However, the backfilling of the gap between the PEM and the tunnel wall must be practical and have required quality, so water inflow control (grouting) may be required and backfilling technology needs to be demonstrated [93].

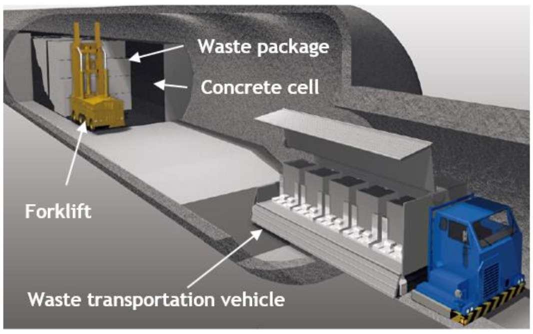
These procedures require remote-handling, because the gap between the PEM and the disposal tunnel wall is insufficient to provide a safe working environment for workers, even if the radiation exposure is sufficiently low.

(2) TRU waste

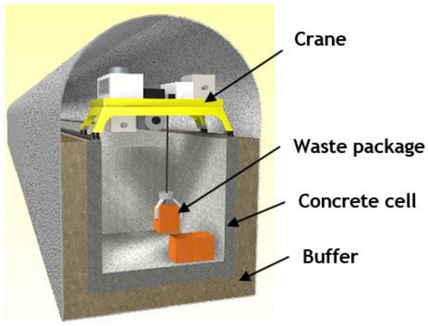
TRU waste packages may be transported underground from surface facilities by an access ramp or shaft. When co-locating with HLW, dedicated TRU access and transport vehicles would be planned [1]. In case of manual operation, the transfer vehicle is provided with radiation shielding. As for HLW, road transportation vehicles such as trucks are assumed for transportation in ramps and tunnels to the disposal vaults [1].

As an alternative method for transportation underground, an access shaft can be considered, as in existing repositories for similar waste, such as the Waste Isolate Pilot Plant (WIPP), a TRU waste repository in the United States [94], and the licensed Konrad repository in Germany [95]. Transportation by access ramp will, however, be considered as the reference case in this report.

Waste packages are transported directly to the disposal vault (contrasting with HLW, which involves transhipment at the end of the access ramp) [11]. As noted in Section 4.2.4 (1) (i) (f), emplacement is assumed to be by forklift for waste package A or by gantry crane for waste package B (schematically illustrated in Figure 4.4-27). Due to the high radiation dose, these tasks must be performed remotely. For this reason, techniques related to accurate positioning and autonomous control become important. In recent years, such an approach is well supported by advances in relevant technology [91].



(a) Forklift system



(b) Crane system

Figure 4.4-27 TRU waste emplacement

Emplacement using a forklift has been considered in detail previously [10] [11], but the gantry crane system noted as a design option in the TRU-2 report is examined in more detail here. In addition, if a forklift is used, partition walls need to be constructed when waste is present, and thus constrained by radiation exposure guidelines. The crane used for waste package B avoids this problem, as construction of partition walls occurs before emplacement of waste packages.

The work flow for TRU waste emplacement by crane is shown in Figure 4.4-28. After excavation, the bottom buffer is installed, with the side buffer installed after the construction of the structural framework (2).

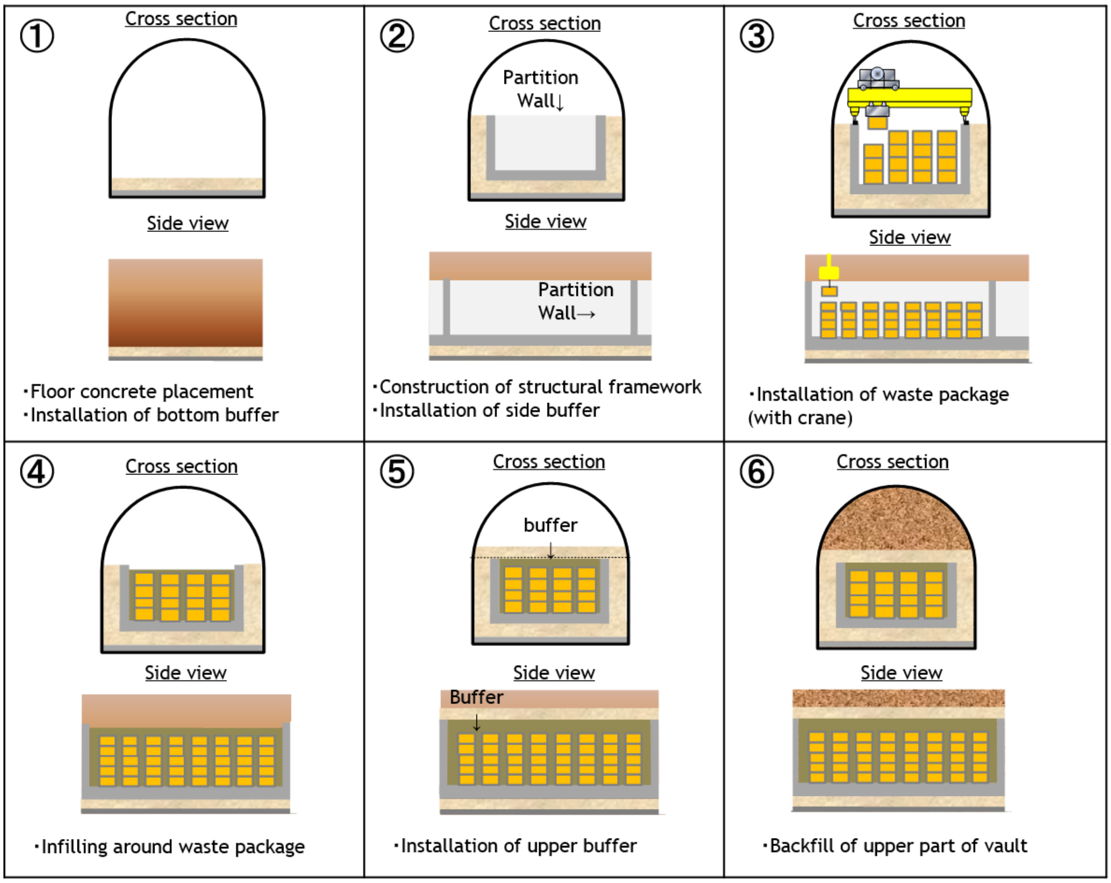


Figure 4.4-28 TRU waste disposal work flow

Figure 4.4-29 shows waste package transfer to the disposal tunnel, unloading by crane from the transport vehicle and moving to a predetermined position in the disposal vault (3).

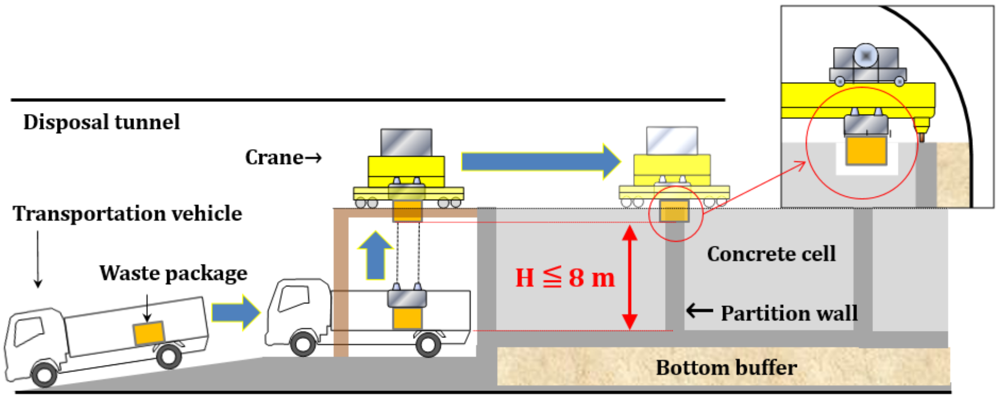


Figure 4.4-29 Transport of waste packages to the emplacement vault. Handling height, H, set as limit for waste packages (see Section 4.5.2 (2) (i) (c)).

After filling an emplacement cell with waste packages, it is infilled (4). After the entire vault is filled, the upper buffer (5) is installed and remaining roof space backfilled (6) (see Section 4.5.3 (1)). Full-scale demonstration tests of several of these operational steps have been carried out [20] [48] [85] and associated construction technology is summarised in Supporting Report 4-31. From technological development to date, it is concluded that EBS construction and associated quality control techniques to achieve the target performance is considered practical.

4.5 Design of underground facilities

In this section, the design of the underground facilities is described, based on the SDMs developed in Chapter 3. In addition, the required engineering technology and safety measures for underground construction, operation, and closure are assessed, for both normal operations and potential perturbations (abnormal states), with a focus on countermeasures to provide defence in depth.

4.5.1 Concept of repository design

(1) Design procedure of underground facilities

The underground facilities of a repository for co-disposal of HLW and TRU waste include the components summarised in Section 4.2.3 (3). As specified in Section 2.1.1 (4), the Final Disposal Plan envisages emplacement of 40,000 canisters of HLW at a rate of approximately 1,000 per year. Thus, the HLW disposal requirements are similar to those in H12, with stepwise construction and operation assumed to run in parallel within specific panels of disposal tunnels. TRU waste packages are emplaced in a more compact manner in larger vaults that have a much smaller total length than the HLW tunnels. For this reason, it is assumed that the TRU waste emplacement is started only after construction of all disposal vaults and it is currently assumed that each waste group will be placed in a dedicated vault. Nevertheless, since the actual TRU inventory is uncertain, allowance is made for later expansion of the vault network. In addition to the design of disposal tunnels and vaults, all other tunnels and galleries required for construction and operation, plus the backfilling and plugs used to close them, must be considered.

For HLW, interim storage for 30 to 50 years prior to disposal has been considered. The footprint of the repository is larger in the case of 30 years storage, in order to minimise the risk of thermal alteration of bentonite buffer. A larger repository may lead to a larger impact to the deep geological environment during the construction and operation of repository. Thus, to minimise such impact, a reference case assuming HLW stored for 50 years is selected (see also Section 4.2.2 (1)).

The process of overall design of the repository is illustrated in Figure 4.2-1, which is expanded in more detail for underground facilities in Figure 4.5-1. The underground facilities will be designed in the following steps: (1) design of tunnels, (2) design of backfill materials and plugs, (3) design of underground facility layout, and (4) design of infrastructure such as drainage and ventilation systems.

The tunnel design defines the cross-sectional shape and dimensions of the different access ways, tunnels and vaults required, based on the installation depth set in Section 4.3 and an evaluation of cavity stability. In the design of backfill materials and plugs, the specifications of materials, structures and installation positions are set based on consideration of groundwater flow characteristics of the excavation damaged zone (EDZ) around tunnels (and boreholes).

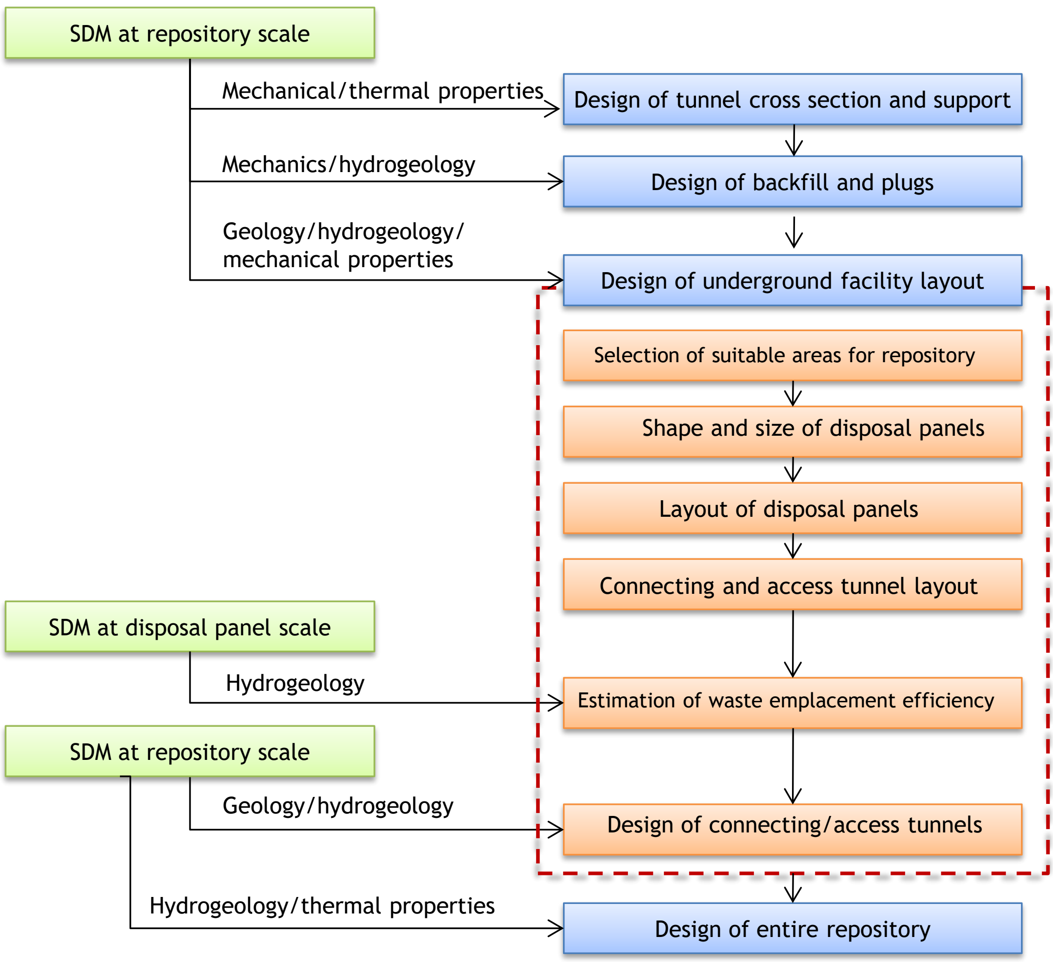


Figure 4.5-1 Repository design flow

For layout design, the tunnel, backfill and plug specifications are extended to include the size and shape of the disposal panels and their spatial arrangement, together with required connecting tunnels, access ramps, shafts, etc. As described in Section 4.2.2 (1), the layout assumes co-location of disposal facilities for HLW and TRU waste, benefiting from sharing site characterisation efforts and surface facilities. In this case, it is necessary to minimise any interactions between these disposal areas [10] [11]. Finally, main services including ventilation, cooling, drainage, power, etc., are considered for the set repository layout, although only at a simple level appropriate to the current design stage.

(2) SDMs for the design of underground facilities

For the design of underground facilities as shown in Figure 4.5-1, key input is provided by the SDMs shown in Section 3.3.3. The SDMs include geological structures, hydrogeology, thermal and mechanical characteristics of bedrock and groundwater chemistry, specifically intended to provide the necessary input for designing the repository.

For tunnel design, the geological characteristics summarised in Table 4.2-6 are used for the evaluation of cavity stability. As shown in Sections 3.3.3 (4) (i) (b) and (c), the SDMs for Neogene and Pre-Neogene sediments are characterised by fold structures, which can be assumed to be associated with stress anisotropy, which has to be considered when designing tunnels with respect to their orientation. Whilst not strictly true, plutonic rocks are treated as having no stress anisotropy in this assessment, as this would be expected to be less of an issue here. Backfill plug designs are based on hydrogeological data presented in Table 4.2-7 and groundwater chemistry from Table 4.2-8, in addition to the rock mechanical data from Table 4.2-6.

The repository layout is defined for each of the 3 SDMs from Section 3.3.3 (4), with particular focus on the structural and hydrogeological model components. Section 3.3.3 (3) discusses the role of large faults and fractures as major groundwater migration pathways, classifying the lengths of faults as an index of significance in the repository scale and panel scale SDMs. Generally, the frequency of faults is inversely proportional to their length. Classification of faults and their handling in design are summarised in Table 4.5-1.

Table 4.5-1 Classification of faults and fractures

Classification of faults and cracks	Representation in SDM (see Section 3.3.3 (3) (i) (a))	Handling in design of underground facilities
> 10 km	Assumed to be an active fault. Treated as a fault excluded from the repository area during LS or PI. Described in regional scale SDM, but excluded from the model area at the repository scale.	From active fault definition, does not apply to the examination of repository layout.
1 - 10 km	Position and characteristics can be roughly determined during LS or PI. Fault distribution is described in regional-scale and repository-scale SDMs.	Disposal tunnels are not placed in areas where such faults are found, as there may be problems with excavation due to mechanical instability, high water inflow, etc. This can be classified as a layout determining feature (LDF).
< 1 km	Because of wide distribution, not realistic to detect all during LS or PI, but can be described in terms of a statistical distribution. Faults described statistically in panel scale SDM.	Considered in planning the disposal area. The hydrogeological and mechanical characteristics of such faults may vary considerably. Since these may require substantial reinforcement or result in ingress of water, tunnels/vaults around intersections of these may be unsuitable for waste emplacement, which needs to be considered when planning the repository layout. This can be classified as an emplacement determining feature (EDF).

Faults of 10 km or more in length are described in the regional scale SDM but, in this report, they are assumed to be excluded from siting area considered on the basis of the initial LS or the PI, and are thus not present in the repository scale SDM (see Section 3.3.3 (3) (i) (a)) and not treated in design.

Faults with a length of 1 to 10 km are described in both the regional scale and repository scale SDMs and it can be assumed that their locations will be determined during LS and PI characterisation (Section 3.3.3 (3) (i) (a)). Concrete examples are shown in Section 4.5.4 (1), but, from the viewpoint of facilitating construction and operation, the layout should avoid such faults to the extent possible, setting disposal panels in areas where they are not present. These thus act as layout determining features (LDF).

Although faults and fractures less than 1 km in length can be located by observation of tunnel walls, they have a high density and it is not possible to detect and characterise them all (Section 3.3.3 (3) (i) (a)). In the repository-scale SDM, the effects of such small faults and fractures are included in the properties of the rock matrix, as these features should be considered in decisions on emplacement of waste and EBS design (so called emplacement determining features: EDF). In the smaller, panel-scale SDM, these are represented by a statistically-generated discrete fracture network (DFN) model. This was used to assess to what extent the variability of the inflows resulting from these fractures would affect the number of suitable disposal locations (see Section 4.5.4 (5) (iv) (b) for further details). The hydrogeological models are used to characterise local variations in groundwater flux, flow velocity and transport path to the accessible environments. In general, low fluxes/flow velocities and long path lengths are favourable.

4.5.2 Tunnel design

In the design of tunnels, key issues are the cross-sectional shape, the support system used and pitch between tunnels. Here tunnel is used as a general term to cover all larger excavated openings – including shafts, ramps, galleries and vaults.

(1) Tunnel design requirements and evaluation items

Tunnel requirements (safety functions) for operational safety include design factors for maintaining a suitable working environment, prevention of occurrence/expansion of accidents, avoiding risks to occupational safety and health, and ensuring alternative escape routes (see Table 4.2-3). To assure the requirement of engineering practicality, the design should show methods of construction, operation and closure based on existing (or soon to be realised) technology. These functions depend on the role of different types of tunnel, as summarised in Table 4.5-2 for the reference case.

Table 4.5-2 Roles of repository tunnels

Function	Access ramp	Access shaft	Connecting/surrounding/ approach tunnel	Disposal tunnel/vault
Transport of waste materials and operational equipment	○	-	○	○
Pathway for workers	-	○	○	-
Pathway for construction machinery	-	○	○	-
Transportation path for excavated rock	-	○	○	-
Ventilation route	○	○	○	-
Drainage/water supply route	-	○	○	-
Power supply and communication path	-	○	○	-
Emergency evacuation route	○	○	○	-

Considering the role of each of these tunnels, design requirements are defined as shown in Table 4.5-3. The available space requirement depends on the role of each tunnel and is ensured by setting an appropriate inner cross-section. For parallel construction and operation, access and connecting tunnels should be designed and laid out to allow movement of machinery, materials and workers without risk of inadvertent or deliberate bypassing of strict zoning between active and non-active areas.

Table 4.5-3 Tunnel design requirements

Design requirements	Objectives	Specifications
Space	Assuring the space required for transport in the tunnel or the installation of engineered barriers, plus equipment necessary for construction and operation, and utilities such as ventilation and drainage	Tunnel shape, inner diameter, inner structures (e.g. drains, cable ways)
Securing safe passage	A safe passage should be assured for sections where workers are present	Tunnel shape, inner diameter, layout
Cavity stability	The mechanical stability of the tunnel should be assured so that construction and operation can be performed safely and efficiently (also considers the thermal stress induced by the waste)	Tunnel shape, inner diameter tunnel lining/support, waste disposal pitch, pitch between disposal tunnels
Reduction of thermal impacts	The performance of the engineered barrier is not significantly reduced due to the heat effect from the waste	Pitch between disposal tunnels, waste disposal pitch
Prevention of rock spalling	Prevention of rock fall	Tunnel support/lining

To meet these requirements, tunnel designs should ensure mechanical stability during construction, operation and closure and also avoid any other potential perturbations, e.g. due to high water inflow. For the specific case of heat-generating waste, reduction of thermal impacts is set as a design requirement.

Table 4.5-4 identifies seismic stability as an evaluation item to assure mechanical stability of tunnels in the case of major earthquakes.

Table 4.5-4 Tunnel evaluation item

Evaluation item	Objective
Seismic stability	The mechanical stability of the tunnel is assured in the case of earthquake motions

In the design of the cross-section of the tunnels, firstly the required inner space will be set, based on the equipment and services to be installed inside the tunnels, clearances for operating machines or material transporters, and the required safe pathways for workers. Then tunnel stability will be analysed, to determine the necessity of tunnel support and constraints on excavation procedures [96] [97]. Here, in the case of the disposal tunnels, a number of parallel tunnels are included in a disposal panel and their pitch must be set to assure both mechanical stability and absence of significant thermal impacts. Specifically for HLW, the pitch of waste package emplacement has also to be considered.

The design of these tunnels is carried out for all three representative host rocks but, as mentioned in Section 4.2.5, mechanical and thermal properties of plutonic rocks and Pre-Neogene sediments are effectively the same (see Supporting Report 4-3) and hence these can be considered together. In terms of an excavation method that is adaptable in terms of cross section, profile and geology, the cost-effective NATM (New Austrian Tunnelling Method) is assumed. A TBM (tunnel boring machine) may be also applicable if the target rocks are suitable for this technique. The tunnelling method will be chosen when tailoring to site properties.

(i) Assessing the tunnel cross section

Standard tunnel profiles considered are horseshoe shaped or circular [98], based on excavation practicality and mechanical stability constraints. For many tunnels a flat floor is required. However, depending on the combination of the size of the tunnel and the strength of the rock, it may be difficult to assure stability at the intersection of the floor surface and the sidewall for a U-shape option. In such a case, stability considerations lead to a tailored horseshoe or circular profile, selected according to the specific conditions. When adopting these cross-sectional shapes, a flat concrete floor is emplaced. Shafts with circular profile are the norm for any deep excavation. Based on the such concerns, an appropriate tunnel cross-sectional shape is selected.

Supporting Report 4-32 describes in detail the process of designing tunnel liners [96] [97]. Such design considers also the impacts of pitch on stability for the specific case of disposal tunnels. The lining concrete specification is derived with explicit consideration of the length of time the tunnel is open, its dimensions, etc.

(ii) Assessing the disposal tunnel pitch

As noted above, a number of parallel tunnels are included in a disposal panel and their pitch must be set to assure both mechanical stability and absence of significant thermal impacts Therefore, tunnel stability analysis assessed the impact of pitch for different shapes and sizes of disposal tunnel cross section, together with the specifications of liners, as described in Supporting Report 4-33.

In addition, for H12V, disposal holes are drilled at regular intervals and the pitch of these has to be selected so that they do not affect each other.

For higher thermal output TRU Grs.2 and 4H, in addition to confirmation of mechanical stability, thermal impacts require consideration when setting vault pitch. For such waste, and also HLW, thermal conduction analysis allowed the assessment of the impact of pitch on maximum temperature, as described in Supporting Report 4-14 (100 °C limit assumed). From these results, the larger of the values of the pitch required to meet stability and thermal constraints is selected.

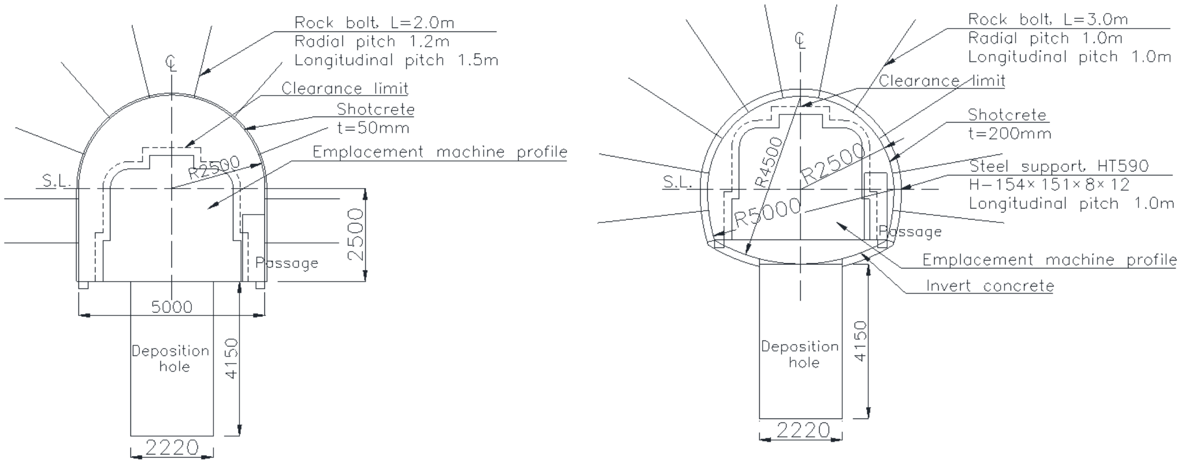
(2) Setting tunnel cross sections

Disposal tunnels and vaults comprise most of the repository volume and these, together with other supporting tunnels, are now specified in terms of cross-sectional shape and dimensions, together with associated mechanical support structures/lining.

(i) Disposal tunnels

(a) H12V

H12V involves placing overpacks containing HLW and surrounding buffer in regularly spaced boreholes. Figure 4.4-18 (a) presented the specification of disposal holes with an inner diameter of 2.22 m and a depth of 4.15 m. The factors that set the construction limits that determine the cross section of the disposal tunnel are the size of disposal hole drilling rig and the overpack/buffer emplacement machine, resulting in the profiles shown in Figure 4.5-2.

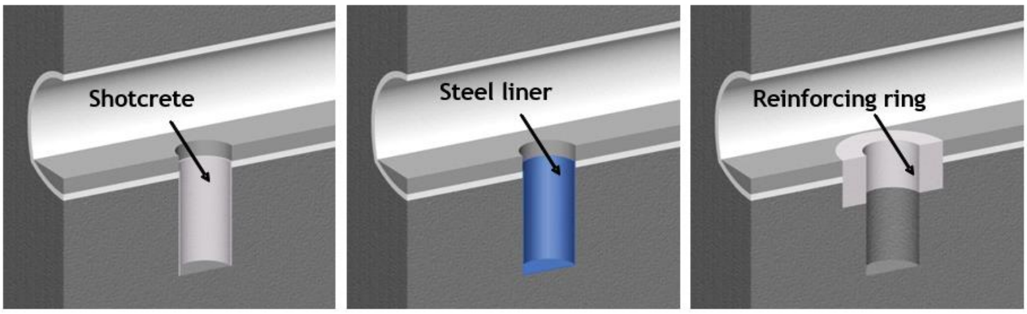


(a) Plutonic, Pre-Neogene sediments **(b) Neogene sediments**

Figure 4.5-2 Disposal tunnel size, cross section and support (H12V)

Mechanical support for Plutonic rocks and Pre-Neogene sediments is based on standard guidelines [98], involving 50 mm thick shotcrete and rock bolts with a length of 2 m and separation of 1.2 m in the circumferential direction and 1.5 m along the tunnel. In the case of Neogene sediment, the same guidelines [98] and stability analysis lead to 200 mm shotcrete and high-standard steel support (HT 590: high strength H-shaped steel with 590 MPa tensile strength) at 1 m intervals along the tunnel. Rock bolts 3 m long have a separation of 1 m in both the circumferential direction and along the tunnel. Stability evaluation of HLW disposal tunnels is described in detail in Supporting Report 4-34.

Disposal holes need to be mechanically stable until the placement of the buffer is complete. Based on the mechanical analysis, such stability is questionable, particularly around the upper part of the hole. It is possible that the design of the hole could be modified to address such concerns (Figure 4.5-3), including a shotcrete or steel liner, or an upper concrete reinforcing ring.



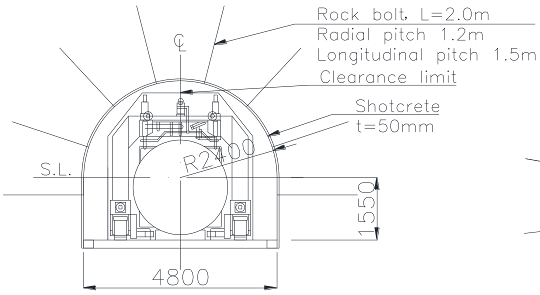
(a) Shotcrete **(b) Steel liner** **(c) Reinforcing ring**

Figure 4.5-3 Hole support to ensure stability
(Source: NUMO, 2011 [1])

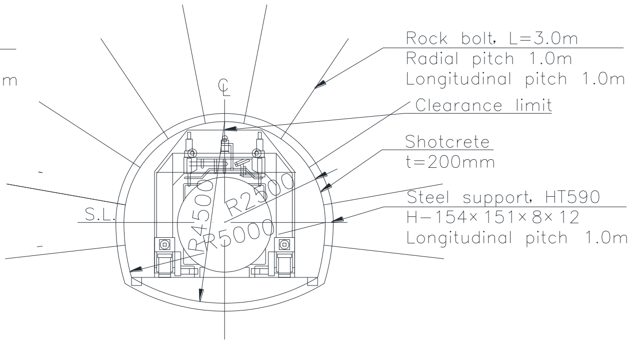
This would, however, both complicate hole excavation and require further materials to be considered in the post-closure safety assessment. For this report, it is assumed the hole would be stable without such support.

(b) PEM

Assessment of the required disposal tunnel cross-section is based on the PEM specification (Figure 4.4-18) and the emplacement machine described in Supporting Report 4-30, with consideration of clearances and space required for support services, resulting in the profiles shown in Figure 4.5-4.



(a) Plutonic, Pre-Neogene sediments



(b) Neogene sediments

Figure 4.5-4 Disposal tunnel size, cross section and support (PEM)

Mechanical support specification and associated stability analysis are the same as for H12V.

(c) TRU waste

TRU waste disposal vaults contain, in addition to waste packages and other engineered barriers, structural framework and backfill (see Figure 4.5-5 for waste package B disposal concept).

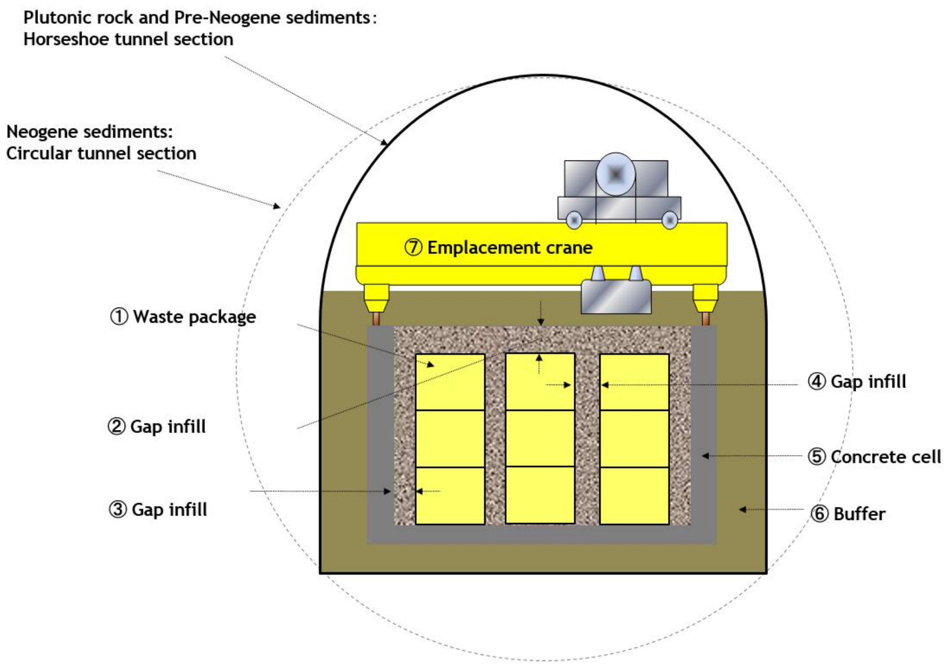


Figure 4.5-5 TRU waste disposal vault

For this reason, the size of the vault is set from the considerations of the density of waste emplacement, thermal constraints, mechanical stability and the design of the structures to be installed for waste handling and emplacement. The design of the TRU waste disposal vault thus involves (1) selection of vault shape, (2) design of required structures (3), establishing construction limits, and (4) determining tunnel cross section shape and support with consideration of the excavation procedure involved. A basic horseshoe shape cross section is selected for plutonic rocks and Pre-Neogene sediments, for further analysis in Section 4.5.2 (1) (i). For weaker Neogene sediments, cavity stability considerations lead to a choice of a circular shape.

As shown in Figure 4.4-28 and discussed further in Section 4.5.5, vault contents include waste packages, infill between waste package and the structural framework, a buffer (in some cases), and a gantry crane required for emplacement. The following assesses the number of waste packages that can be emplaced for different designs of the structural frame and the constraints set by the emplacement crane.

As the density of waste packages is not limited by heat generation for Grs.1, 3 and 4L, waste package emplacement density focuses on meeting required storage capacity for minimum excavation volume. As shown in Table 4.5-5, different emplacement options in terms of number and height of waste package stacks require different total excavated volumes, allowing the most efficient to be selected.

Table 4.5-5 Low heat waste inventory and excavation requirements

Waste Group	Stacks	Height	Packages per section	(1) Cross sectional area (m^2)	(2) Tunnel length (m)	(3) Volume of additional excavation (m^3) *3	Total volume (m^3) 1 × 2 + 3	Judgement
1*1 (Drum)	4	4	16	129	68.2	5,364	14,162	✓
	4	5	20	150	57.5	7,122	15,747	
3 (Drum)	5	5	25	144	539.1	-	77,630	
	6	5	30	161	459.0	-	73,899	✓
4L (Drum)	5	5	25	147	460.2	-	67,649	
	6	5	30	168	390.7	-	65,638	✓
4L*2 (Box container)	3	4	12	99	65.0	3,168	9,603	✓
	4	4	16	113	54.5	4,401	10,556	
	5	4	20	134	48.5	6,047	12,546	

*1 Gr.1: includes buffer and its volume is also considered.

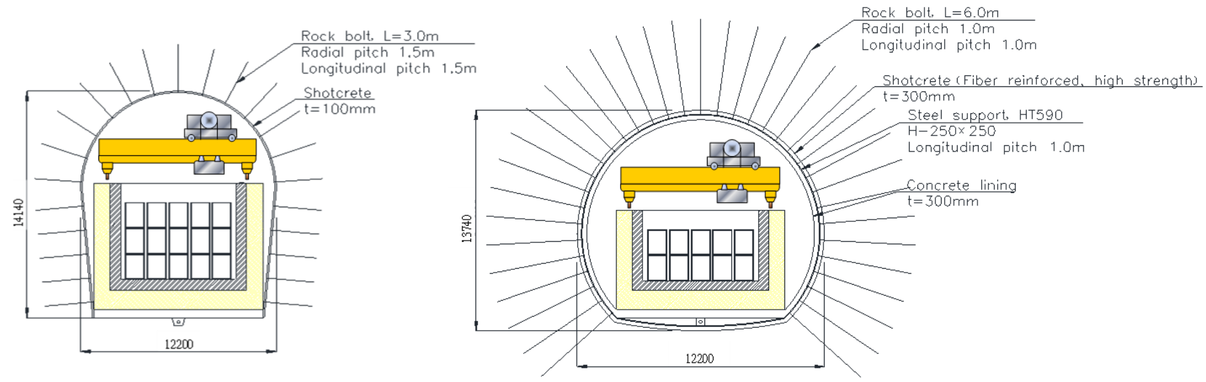
*2 Gr.4L: since the dimensions of the waste package are different for drums and box containers, separate disposal tunnels are considered.

*3 Gr.1, 4L: box container vaults are dead-end because the quantity of waste is small and the tunnel length is short. Therefore, a widened section was provided between the connecting tunnel and the disposal vault to allow for this.

Vault profiles for higher heat output Grs.2 and 4H are also assessed in the light of efficiency of use of excavated volumes. However, as noted in Section 4.2.4 (2) (ii), infill between waste packages could be thermally degraded (even if this is rather unlikely on the basis of current knowledge) and a buffer outside of the structural framework is included to assure safety functions. In addition, in order to prevent thermal degradation of the buffer, the waste package density was set so that the temperature of the buffer material did not exceed 100 °C (again very conservative based on current understanding). Further, the spacing between waste packages was set to 150 mm in consideration of ease of mortar infilling.

The structural framework forming the disposal cells (manufactured from reinforced concrete) is designed based on the selected waste package emplacement scheme and wall thickness requirements to support the gantry crane (Section 4.4.3 (2)), providing structural integrity against loads such as self-weight, fluid pressure at the time of infilling and swelling pressure of buffer. Details are provided in Supporting Report 4-35. From the designs, the height of the side wall of the structural framework ranged from 4.05 to 7.95 m. Based on this, as described later in Section 4.5.6 (1), the maximum waste package handling height when lifting by crane was set to 8 m.

Figure 4.5-6 illustrates examples of tunnel profile, dimensions, structural framework, buffer and structural support for Gr.2 in the hard and soft rocks.



(a) Plutonic rock, Pre-Neogene sediments **(b) Neogene sediments**

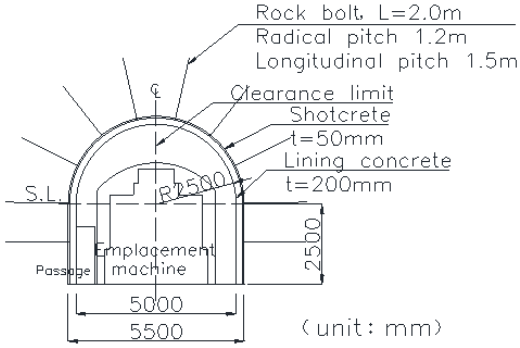
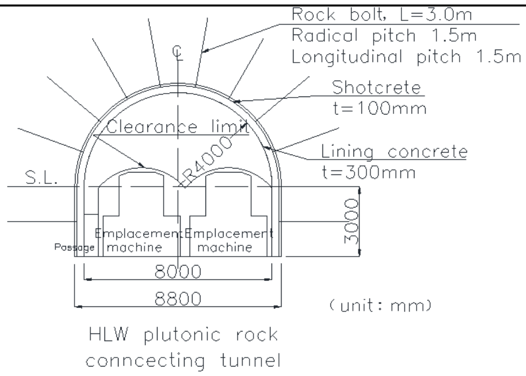
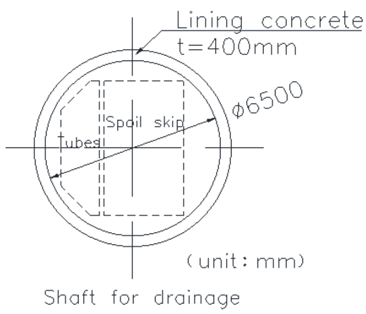
Figure 4.5-6 Examples of TRU waste disposal vault cross sections (Gr.2)

Specifications for the other waste groups are provided in Supporting Report 4-36. Cavity stability evaluation results (see Supporting Report 4-37) show that the excavation method and provision of mechanical support is important, particularly for Neogene sediments, when excavation in a number of steps is required to assure release of drilling stresses without risk of wall failure.

(ii) Other tunnels

Table 4.5-6 summarised the basic design assumptions for other types of tunnel, with an example of resulting specifications for H12V/TRU in plutonic rocks (more details in Supporting Report 4-38). A key constraint on dimensions is set by logistical aspects, determining whether tunnels need to handle one- or two-way traffic. The size of transported waste packages (especially H12 overpack or PEM) needs to be considered, along with additional clearance for services. Such clearance would, for example, be needed for electrical supply, ventilation ducts and safe passage for evacuation in case vehicles block the tunnel. However, different technical solutions to meet requirements would impact the resultant dimensions of the tunnel. The current dimensions are thus indicative of what is needed, but may be optimised in the future by considering all necessary functions of the tunnel, as well as the cost of excavation and eventual backfilling. Such studies would be needed for detailed, site-specific design of the repository.

Table 4.5-6 Assumptions and specifications for other tunnels (H12V and TRU waste in plutonic rock)

Tunnel type	Design assumptions	Specification example (plutonic rocks)
Surrounding tunnel (HLW)	Based on H12V with 5 disposal tunnels operating in parallel to provide the required 5 overpacks/day throughput Daily transport rate is low and hence 1 lane is sufficient.	
Connecting tunnel (HLW)	Requires 2 lanes so that the overpack and buffer emplacement device can pass each other	
Approach tunnel (TRU)	Because there is limited material associated with loading waste packages into individual vaults, one lane is sufficient	Same cross section as the surrounding tunnel (HLW)
Surrounding tunnel (TRU)	Because there is a large material flow to all vaults, 2 lanes are required to allow for waste delivery and return of transport vehicles.	Same cross section as the connecting tunnel (HLW)
Access shaft (HLW · TRU)	Critical for material transport in large quantities at the time of construction (e.g. removal of excavation spoil and supply of concrete). It is also important for utility supply, such as ventilation and drainage. In addition, space is also required to secure a work platform for drilling the shaft itself.	
Access ramp (HLW · TRU)	In order to transport over long distances at low speed (safety considerations), two lanes are required to allow for waste delivery and return of transport vehicles.	Same cross section as connecting tunnel

Since the specification of the connecting tunnel cross section here is the same as the HLW disposal tunnel, the specifications of the mechanical support structure are also the same. The access ramp and the connecting tunnel have a 3 m larger width than the surrounding tunnel, and the standard support can be applied to ensure cavity stability. These tunnels operate for a relatively long period, from the initial stage of construction to closure, which is explicitly considered when specifying concrete lining requirements. In addition, in order to reduce impacts of water inflow, a waterproof sheet is included between the initial shotcrete support and the final concrete lining (details in Supporting Report 4-38).

(3) Setting the pitch of disposal tunnels and holes

(i) Assessment of cavity stability

To assess mechanical stability, based on the H12 approach, the width of the plastic area of rock surrounding a tunnel is obtained by two-dimensional or three-dimensional finite element analysis, with consideration of the process in which mechanical support is emplaced during construction (see details in Supporting Report 4-34). For H12V, meeting the stability criteria requires a tunnel pitch of at least 2D (where D is the tunnel diameter) for plutonic rock and 2.4D for Neogene sediments (i.e. 10 m and 12 m, respectively for D = 5 m). Disposal pitch is set on the basis of approach to shear breakdown when the local safety factor is 1.2 or less. Applying this criterion, the minimum hole pitch is 2d (d: disposal hole diameter) for plutonic rock and 3d for Neogene sediments (i.e. 4.44 m and 6.66m, respectively, for d = 2.22 m).

For the PEM system, the same results apply in terms of tunnel pitch, but differences in the diameter of the disposal tunnels need to be considered (see Section 4.5.4 (2) (ii) (b)). Thus, 2 D pitch for plutonic rocks corresponds to 9.6 m while 2.4D for Neogene sediments corresponds to 12.0 m.

Evaluation of the cavity stability of TRU waste disposal vaults was performed by elasto-plastic analysis considering the stepwise excavation appropriate to such a large cross-sectional area (details can be found in Supporting Report 4-37). For plutonic rocks, tunnel inner diameter (D) ranges from 9.64 m ~ 12.69 m depending on the waste group, and a disposal vault pitch of 2.5D was initially set to meet cavern stability criteria. For Neogene sediments, it is difficult ensure stability compared to the case of the plutonic rocks. Thus, two specific cases, D = 13 m or 16 m, were analysed in detail for a vault pitch of 3D. In both cases extensive support was required, despite drilling stress relief during stepwise excavation and support emplacement (2 steps for D = 13 m, 5 steps for D = 16 m). In both cases, 30 cm thickness of shotcrete was required together with high standard steel support (H-200 and H-250, for the small and large tunnel respectively).

(ii) Assessment of thermal effects

(a) H12V

Thermal effects were assessed for plutonic rocks (depth 1,000 m) and Neogene sediments (depth 500 m), extending the stability studies from Section 4.5.2 (3) (i), with details summarised in Supporting Report 4-39. For plutonic rocks, the minimum pitch to ensure stability of tunnels (2D, 10 m) and emplacement holes (2d, 4.44 m) were subject to heat conduction analysis. It was confirmed that the buffer temperature limit of 100 °C was not exceeded for HLW that had been in interim storage for 50 years and hence these pitch values met all criteria (see Section 4.5.1 (1) for further explanation).

For Neogene sediments, the minimum pitch to ensure stability of tunnels (2.4D, 12 m) and boreholes (3d, 6.66 m) were also subject to heat conduction analysis. Again, it was confirmed that the buffer temperature limit of 100 °C was not exceeded and hence these pitch values met all criteria. In addition, in this case the criteria were met for both 30 and 50 years of interim storage, as shown in Table 4.5-7.

(b) PEM

It is assumed that PEMs are emplaced in contact with each other (effective waste pitch 3.36 m) and hence the only variable considered for thermal analysis is the disposal tunnel pitch (details in Supporting Report 4-40). Figure 4.5-7 shows the relationship between disposal tunnel pitch and the maximum buffer temperature for HLW stored for a 50-year period in plutonic rock. Minimum pitch to ensure the cavity stability (9.6 m) results in buffer temperatures slightly above 100 °C (Figure 4.5-7), while this limit is not exceeded for a pitch of 11 m.

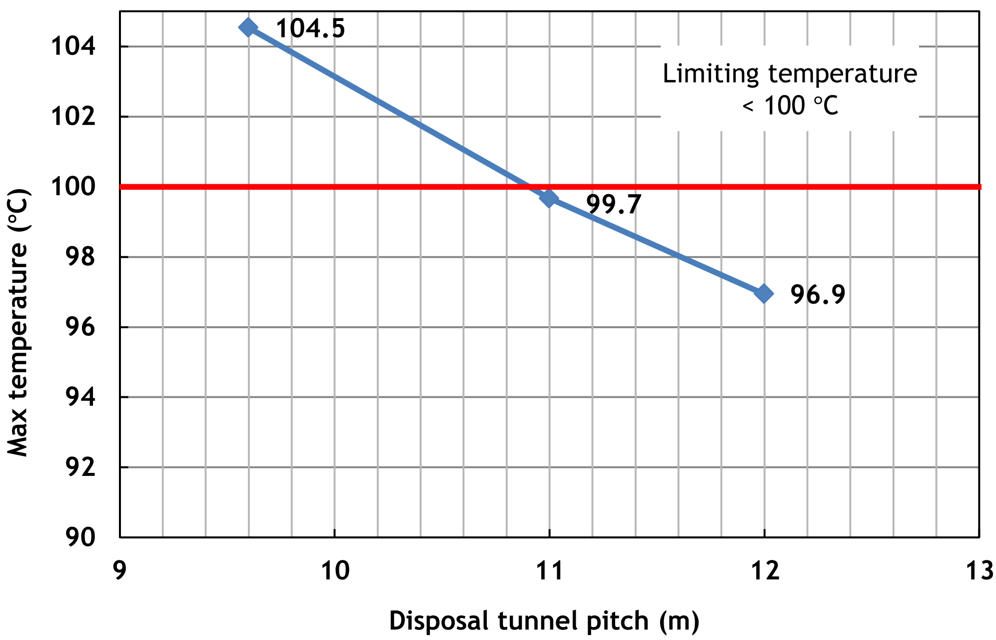


Figure 4.5-7 Relationship between tunnel pitch and maximum buffer temperature (PEM, Plutonic rock)

It should be emphasised that this is an extremely conservative treatment, as the excess temperature is minor and lasts only a few decades, during which the steel handling shell would probably be intact – making the contained bentonite even less vulnerable to higher temperatures. For Neogene sediments, the minimum pitch of 12 m to ensure stability of tunnels results in a maximum buffer temperature < 100 °C and hence this pitch met all criteria. Again, the criteria were met for both 30 and 50 years of interim storage, as shown in Table 4.5-7.

(c) TRU waste

Thermal effects resulting from TRU waste disposal were assessed as for the HLW case Based on the configuration of disposal vaults presented later in Section 4.5.4 (2) (iii) (b), vaults for higher heat generating TRU waste are interspersed with those with a lower heat loading to reduce thermal effects on both the EBS and contained waste. The pitch of vaults was initially determined on the basis of mechanical stability, and then assessed to check if temperature limits set for buffer or mortar infill between waste packages are exceeded. The thermal analysis is carried out in two steps, first simple heat-conduction calculations to assess the sensitivity of temperature to vault pitch and then, when the pitch from mechanical constraints appeared suitable, more detailed analyses were performed to determine detailed temperature profiles within the vaults for this pitch. The following presents examples of results obtained from the latter analyses (further details in Supporting Report 4-41).

Figure 4.5-8 shows the evolution of the thermal transient, evaluated at the location in the buffer where the highest temperature was observed, for vaults containing the higher heat TRU wastes in plutonic rocks (as the extreme case). The highest temperature was approximately 90 °C, for the highest thermal output TRU waste (Gr.4H, MHHRW). In the case of Neogene sediments (not shown), the highest temperature was 84 °C. Thus, the buffer temperature limit of 100 °C was not exceeded in any case and the highest temperatures are apply to relatively short transients with highest temperatures lasting only a few decades.

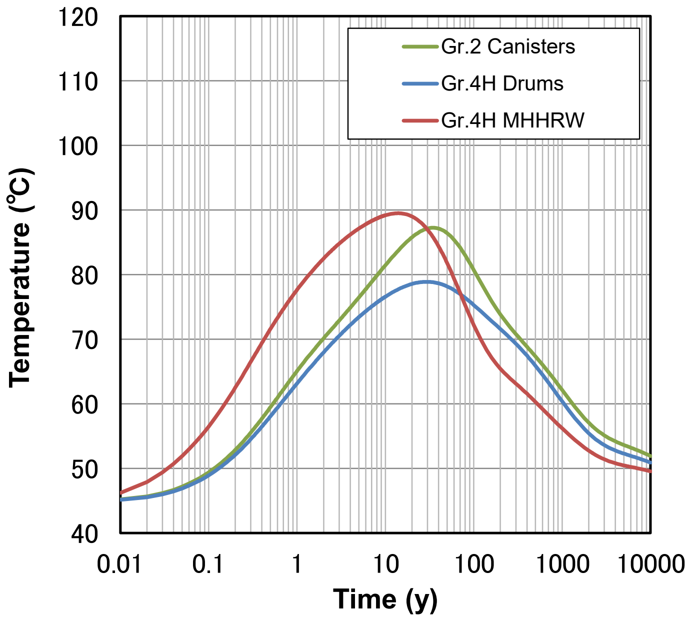


Figure 4.5-8 Time-dependent temperature change in the bentonite buffer for the heat-generating TRU wastes (plutonic rocks)

According to the TRU-2 report, mortar can be denatured at temperatures above 80 °C, although this may be rather conservative on the basis of more recent studies. Thus, in order for the vault infill to retain its sorption safety function, a requirement is set that the temperature should be less than 80 °C. Gr.2 and 4H vault infill lies inside a buffer and, based on the above analysis results, the mortar temperature limit is likely to be exceeded. Thus, the conservative treatment assumes loss of the sorption safety function described in Section 4.2.4 (2) (ii). For other groups (1 and 4L), even taking into account the influence of heat from the Gr.2 and 4H disposal tunnels, temperatures fall below 80 °C. As indicated in Section 4.5.4 (2) (iii) (b), Gr.3 disposal tunnels are isolated from the other waste groups and hence not affected by heat. Therefore, the sorption safety function is applied to vault infill only for Grs.1, 3 and 4L, even though the temperature excess is small with a short duration for the other waste groups and hence this conservatism will be reconsidered in the future.

(iii) Results of setting disposal tunnel pitch

Table 4.5-7 summarises the calculation results of pitch between disposal tunnels described above.

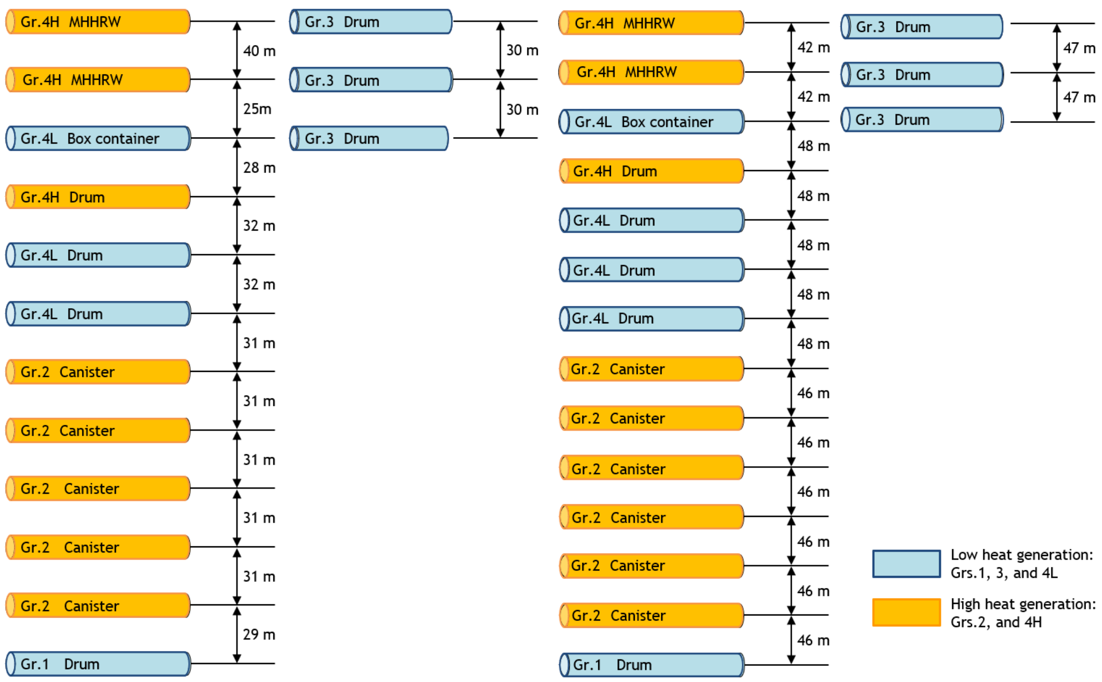
Table 4.5-7 Results of minimum HLW disposal tunnel pitch evaluation (rounded values in m)

Condition		H12V			PEM		
		Plutonic	Neogene	Pre-Neogene	Plutonic	Neogene	Pre-Neogene
Mechanical stability	Based on diameter of disposal tunnel (≈ 5 m)	10	12	10	10	12	10
	Based on the diameter of the widened entry of the disposal tunnel (≈ 8 m[1])	-	-	16	16	22	16
Thermal effects	Storage period 30 years	18	12	18	22	22	22
	Storage period 50 years	10	12	10	11	12	11
Chosen distance for reference design[2]		10	12	16	16	22	16

[1] The diameter of disposal tunnel is widened from 5 m to 8 m at the entry, due to the turning radius of the emplacement machine for the PEM (Supporting Report 4-50).

[2] Design in the present report focuses on interim storage of HLW for 50 years (see Section 4.5.1 (1)), so this is used to set the pitch and the 30-year storage data are used only to indicate the consequences of shorter storage times.

From the table and the reference 50 years waste storage time, the chosen pitch is set by mechanical stability of tunnel. However, if HLW stored for 30 years is considered, thermal constraints define the selected pitch. For TRU waste, the results of thermal and stability analyses result in distributions of different waste groups and the vault pitches shown in Figure 4.5-9 (see Supporting Report 4-42).



(a) Plutonic rock and Pre-Neogene sediments **(b) Neogene sediments**

Figure 4.5-9 TRU waste group distributions and vault pitch

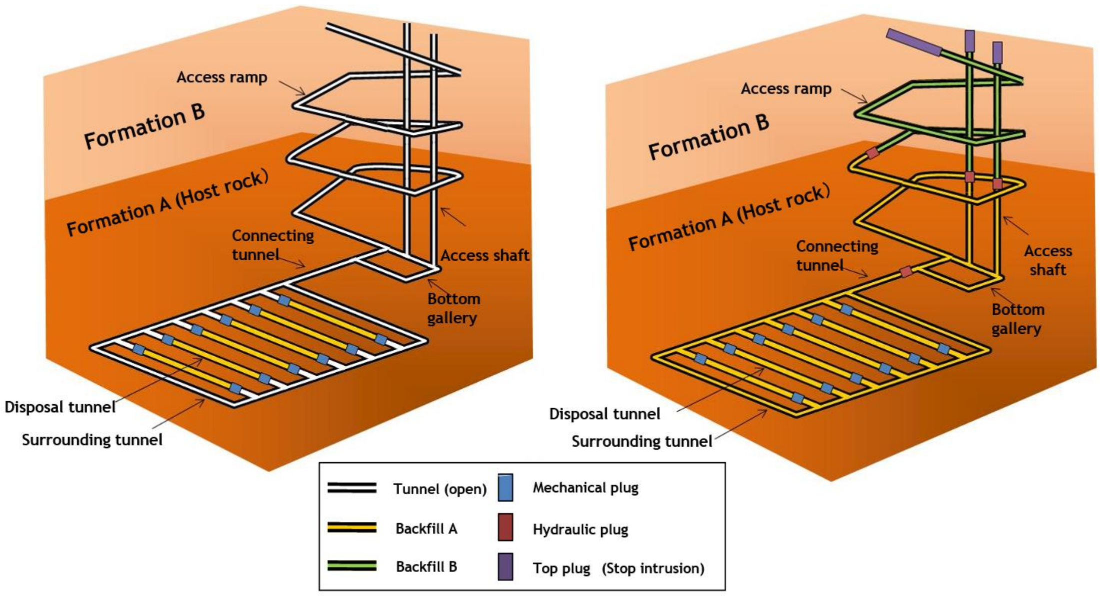
(4) Evaluation of seismic stability

In Japan, where earthquakes often occur, it is necessary for the tunnel to ensure stability not only at the time of excavation but also in the case of earthquake motion. Because the Neogene sediments are the weakest of the three representative rocks, seismic stability was assessed for these as representing the worst case. This showed that the seismic impacts on the local safety factor and the support stress are small, even in the event of major earthquakes, so that the mechanical stability of tunnels is assured during the excavation of the tunnel [99].

For HLW disposal tunnels, the largest observed seismic waves from the 2011 Tohoku Pacific Ocean earthquake were considered for simulating ground motion, showing that the effects of even such a huge earthquake during excavation would still meet the criteria for tunnel stability [100].

4.5.3 Design of backfill and plugs

Backfilling and hydraulic plugs can be considered together as shown in Tables 4.2-4 and 4.2-5, providing the safety function of reducing RN migration by avoiding flow short-circuits. In addition, mechanical plugs are installed at the end of disposal tunnels to constrain free swelling, which decreases the performance of buffer and backfill. The concept of stepwise backfilling and plug installation is illustrated in Figure 4.5-10 for the case of disposal in through tunnels (TT) and only slightly modified for dead-end tunnels (DET).



(a) Operational period
(Backfilling of disposal tunnels and installation of mechanical plugs)

(b) Post-closure
(Backfilling of all tunnels, installation of hydraulic plugs, access sealing)

Figure 4.5-10 Concept for backfilling and plugging for the case of TT

During the operational period, it is necessary to backfill disposal tunnels after waste emplacement and to install plugs to prevent free-swelling of backfill out of the tunnel (Figure 4.5-10 (a)). During repository closure operations all connecting tunnels, the access ramp and shafts are backfilled and hydraulic plugs installed at appropriate locations. In addition, access seals are installed near the surface with the aim of preventing accidental human intrusion (Figure 4.5-10 (b)). Based on the permeability of the surrounding bedrock and EDZ around the tunnel, the backfill material is designed to have sufficiently low permeability to ensure that tunnels do not become preferential groundwater flow paths. More detailed studies of this are ongoing.

For example, as shown in Figure 4.5-9, if the permeability of the rock is different in host rock A and overlying formation B, backfill specifications will be tailored to each of these. To prevent preferential hydraulic pathways along the access tunnel, hydraulic plugs are installed around the ends of these. If there are boundaries between geological formations with different hydraulic properties, hydraulic plugs are also installed near such boundaries. The specification of backfill material and the installation positions of hydraulic plugs will be determined according to the geological environment found.

Below, the design concept and specifications of backfill materials, mechanical plugs, and hydraulic plugs are shown for connecting tunnels, surrounding tunnels and disposal tunnels. For access sealing, a structure combining dense concrete and coarse gravel, which is more resistant to excavation, has been considered to reduce risk of human intrusion [101] [102].

(1) Design of backfill

(i) Design requirements and evaluation items for backfill

Design requirements and evaluation items for backfill are listed in Tables 4.5-8 and 4.5-9. A post-closure safety function relates to restriction of migration of RNs (Tables 4.2-4 and 4.2-

5), which leads to low permeability being a design requirement, along with engineering practicality.

Table 4.5-8 Backfill design requirements

Design requirements	Detailed description of requirement for concepts assessed	Specifications
Low permeability	Tunnel is not a preferential groundwater flow path	Material, effective dry density of clay
Engineering practicality	Ability to manufacture and install to required quality levels based on existing technologies or those which will be realised in the near future	Material, dry density, effective dry density of clay, composition of backfill material

Table 4.5-9 Backfill evaluation items

Evaluation item	Specifications
Restriction of swelling of buffer	To limit the swelling of buffer material and hydraulic plug components (in case of clay plug) after saturation commences

Tunnels backfilled with suitable material should not act as preferential RN migration paths. The location of backfill in disposal tunnels/vaults is illustrated in Figures 4.4-18 and 4.4-25, for HLW and TRU, respectively. For H12V, in the current design without a borehole cap, backfill has the additional function of restricting buffer swelling out of emplacement holes. A similar function applies to backfill materials in contact with hydraulic plugs, whose specification includes a clay barrier with properties similar to buffer (see Section 4.5.3 (3)). Although possibly less critical for performance, backfill will also constrain swelling of PEM buffer after failure of the handling shell. Therefore, as an evaluation item, restriction of buffer swelling is selected to cover all these cases.

After selecting the material to be used for backfill, the density required to satisfy the design requirements has to be specified. This allows it to be assessed for this specification, to confirm that it is appropriate. Here, analysis was performed based on the evaluation of long-term stability of buffer material (more details in Supporting Reports 4-17 and 4-28).

(ii) Specification of backfill materials

In repository construction, a large amount of excavated spoil is generated. Spoil consisting of crushed host rock can be considered as potential backfill, particularly from the standpoint of ease and economy of production [65]. However, it is extremely difficult for crushed rock backfill to meet the goal of having the same low permeability as the original rock. Therefore, mixing bentonite with crushed rock is assumed, which will produce the low permeability required. The particle size of crushed rock is defined from the viewpoint of workability. At this time, chemical changes during surface storage (e.g., acidification due to the oxidation of pyrite) are not considered but, in the future, it will be necessary to confirm that this does not impact performance.

As crushed rock will have specific properties that cannot be defined until specific sites are identified, silica sand is considered as a substitute for backfill specification. Also, bentonite will be represented by Kunigel V1, as for buffer definition. In setting the specification of backfill materials, Na-bentonite alteration by Ca exchange was also considered. Groundwater flow analysis to assess the impact of buffer permeability showed that, below a certain value, flow was unaffected due to the role of the EDZ (details in Supporting Report 4-43). This means that the impact of backfill is inherently limited and that, additionally, hydraulic plugs are required in specific locations. Based on this analysis, the upper limit of hydraulic conductivity of the backfill was set as 10 times the average value of the host rock.

In addition, for the engineering practicality design requirement, a dry density of 1.8 Mg/m^3 was set based on the upper limit that can be obtained by in-situ compaction in a tunnel. Here, the lowest rock hydraulic conductivity (2.0×10^{-9} m/s; Table 4.2-7) is used in setting the required density and composition generally applicable to all rocks. The details of the set backfill specifications are given in Supporting Report 4-43, based on EDZ hydraulic and mechanical properties given in Supporting Report 4-44. Figure 4.5-11 illustrates compaction properties of bentonite mixed with crushed rock (represented by sand or gravel). In general, the mixture becomes less compressible as the density and content of sand increases [103].

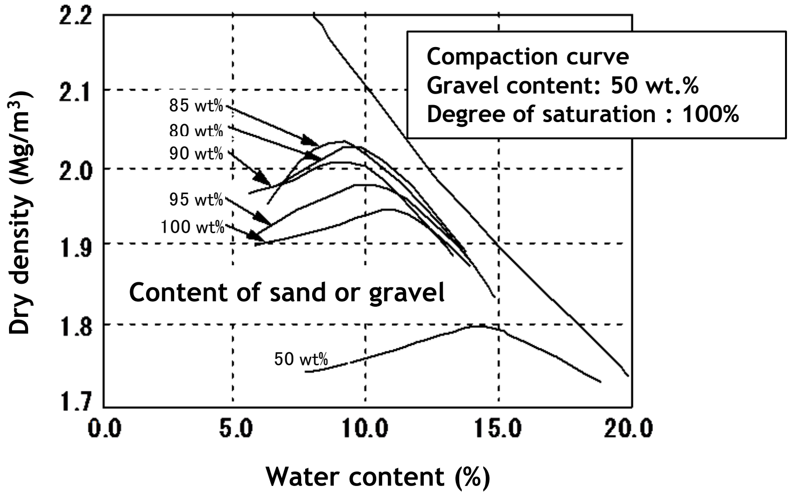


Figure 4.5-11 Compaction curves of bentonite mixed with sand or gravel [65]

From the viewpoint of restriction of buffer expansion, a high density is preferable, but other requirements on the backfill need also to be considered. From Figure 4.5-11, 15% bentonite and 85% crushed rock would give the highest maximum dry density after compaction.

The backfill construction technology for disposal tunnels is considered in Section 4.5.7 (2), while backfilling of other tunnels at repository closure is covered in Section 4.5.7 (3). The method of manually-operated, in-situ compaction is selected in cases without access constraints, while a remote-operated spraying method is considered for areas where worker access is not allowed. To assess engineering practicality, these two methods have been examined (see Supporting Report 4-43). From the above, the backfill specifications summarised in Table 4.5-10 were set for these 2 construction options.

Table 4.5-10 Specifications of backfill

Construction method	Composition	Dry density (Mg/m^3)	Effective clay dry density (Mg/m^3)	Target areas
Compaction	Bentonite 15% Crushed rock 85%	1.8	0.6	Disposal tunnel/vault (H12V/TRU), connecting tunnels, approach tunnel (TRU waste), surrounding tunnels, access ramp, access shafts
Spraying	Bentonite 50% Crushed rock 50%	1.6	1.2	Disposal tunnel (PEM)

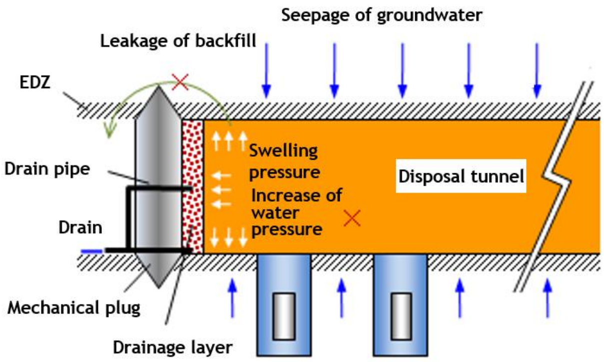
* These reference specifications are derived for silica sand and would be modified to account for the properties of specific host rocks.

For these backfill specifications, the effectiveness of restriction of buffer swelling was assessed by a simple numerical analysis that considers buffer swelling during saturation, assuming that backfill is emplaced before buffer swelling commences. It was confirmed that, in this case, the change in density of the buffer material was slight and remains within the specification range for a long period (details in Supporting Report 4-45). However, the practicality of the operations involved would need re-assessment to confirm acceptable performance on a site-specific basis.

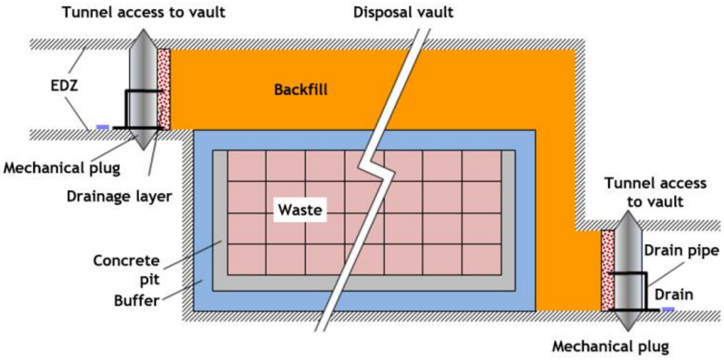
(2) Design of mechanical plugs

(i) Mechanical plug design requirements

Mechanical plugs are planned to be installed at open ends of HLW disposal tunnels or TRU vaults to prevent backfill material from swelling outwards (see Figure 4.5-12).



(a) HLW disposal tunnel (Example of H12V)



(b) Disposal vault for TRU waste

Figure 4.5-12 Concept of the installation position and structure of mechanical plugs

Design requirements for mechanical plugs are structural integrity and engineering practicality, which are given in Table 4.5-11 along with resulting specifications. In order to satisfy these design requirements and to provide a solid structure that can withstand swelling pressure of backfill materials, the plug is assumed to be made of reinforced concrete, since similar plugs have been demonstrated in URLs. The application of other materials (e.g. steel plug) may be considered after more detailed studies to determine installation technology requirements for specific sites and disposal concepts.

Table 4.5-11 Mechanical plug design requirements

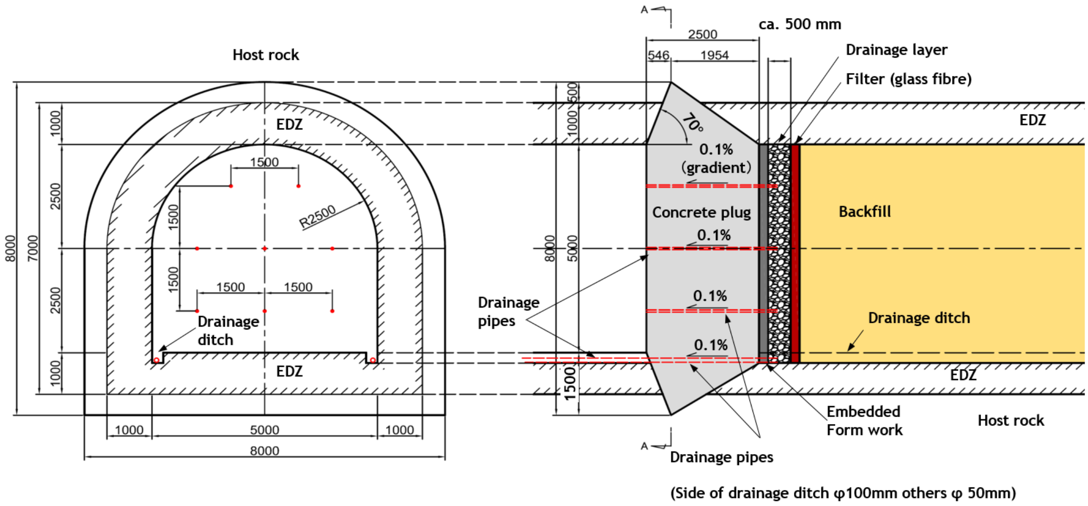
Design requirements	Detailed description of requirements for concepts assessed	Specifications
Structural integrity	Ability to withstand swelling pressure of backfill	Plug thickness, notch shape, reinforcement
Engineering practicality	Ability to construct to required quality levels based on existing technologies or those which will be realised in the near future	Design, formulation and strength of concrete

The mechanical plug concept currently considered does not provide a hydraulic barrier, which would require the ability to withstand high groundwater pressures during construction, although this option might be considered in the future. Thus, a permeable layer is placed between the mechanical plug and the backfill material to facilitate drainage and to reduce the groundwater pressure acting on the plug (see Figure 4.5-12), allowing drainage from the backfilled tunnel during the entire operational period without a risk of backfill erosion.

As the basis for design, the load acting on the plug and the amount of water to be drained from the disposal tunnel have to be defined. The structural specifications and material properties of the plug and associated drainage material are set for these conditions. With regard to the plug body, the generated cross-sectional force and the reaction force from the rock are calculated, with structural integrity examined with respect to the rock strength, sliding force and stress level over the cross section. If the stress levels generated in the rock and plug are below the allowable limits, a concrete composition satisfying the design requirements for construction practicality is set to satisfy the design requirement of structural integrity. For drainage materials, the specifications should ensure sufficient drainage capacity for expected conditions.

(ii) Mechanical plug specifications

Figure 4.5-13 illustrates the structure and dimensions of the reference mechanical plug, although it is recognised that this would need to be tailored to specific sites and disposal concepts.



Cross section of the disposal tunnel **Structural elements and dimensions**

Figure 4.5-13 Design the mechanical plug

Drainage pipes (gradient 0.1%) are installed within the plug, and a permeable layer (crushed rock) is provided on the disposal tunnel side of the plug, enabling efficient drainage during the operational period. At the boundary between the permeable layer and the backfill, a filter material (e.g. glass fibre fabric) is installed to prevent the backfilling material being eroded. The design of this filter and confirmation of its function will require more development work. In addition, an embedded formwork (made of glass fibre reinforced concrete) is used for the installation of the permeable layer and the manufacture of the mechanical plug.

The load acting on the plug results from the swelling pressure of backfill and buffer, creep of rock and any hydrostatic pressure that would result if drainage is insufficient. In particular for TRU waste vaults containing buffer, this underlies the backfill and the total swelling pressure of both acts on the plug. Structural stability calculations have been performed for these set loads for the representative 3 host rocks, using the standard design strength of concrete of 30 MPa, 2.5 m concrete thickness (reinforcement specification D32 @ 150 mm) and a notch depth of 1.5 m. The details of the design of the mechanical plug are given in Supporting Report 4-46.

(3) Design of hydraulic plugs

(i) Design requirements for hydraulic plug

During closure, hydraulic plugs are set at key locations to prevent short-circuit flows of RNs though tunnels. These provide an area with sufficiently low permeability and also block potential pathways through the tunnel EDZ. EDZ hydraulic and mechanical properties are given in Supporting Report 4-44.

Design requirements for hydraulic plugs are shown in Table 4.5-12, which focus on post-closure restriction of RN transport (Table 4.2-4 and Table 4.2-5) due to low permeability, together with the associated engineering practicality requirement.

Table 4.5-12 Hydraulic plug design requirements

Design requirements	Detailed description of requirements for concepts assessed	Specifications
Low permeability	Limit the flow of groundwater along the tunnel and its surroundings in combination with the tunnel backfill	Material, effective dry density of clay, Plug structure
Manufacturability and engineering practicality	Ability to manufacture and install to required quality levels based on existing technologies or those which will be realised in the near future	Design, dry density, mixing ratio of materials

After selecting materials, a specification is developed that satisfies the design requirements. The material specifications (formulation and density) are provisionally set and then the structure of the plug is examined by sensitivity analysis to develop a specification that meets the low permeability design requirement.

Here, by providing notches in the bedrock that exceed the width of the EDZ, the design should block this transfer path of RNs. Since the installation of the notch in the bedrock itself is a new tunnel excavation, a construction method is selected so that no significant EDZ is formed around the notch. The detailed design of this is described further in Supporting Report 4-47, but details would depend on the actual host rock properties.

(ii) Specification of hydraulic plug

The hydraulic plug currently considered is a clay plug in which silica sand is mixed with bentonite, with a material specification that can ensure a low hydraulic conductivity $< \approx 1.0 \times 10^{-10}$ m/s (blending of 70% Kunigel V1 bentonite and 30% silica sand, dry density 1.6 Mg/m^3). Although the construction technology of hydraulic plugs is described in Section 4.5.7 (3), the design developed was based on a stack of compacted bentonite blocks. For this method, practicality and expected performance have been confirmed by full-scale in-situ testing [104]. Further development work may be needed, especially to ensure that the specific plug design is applicable to actual host rock conditions.

Figure 4.5-14 illustrates the structure and dimensions of the hydraulic plug. It is manufactured by cutting notches into the tunnel to form two walls (thickness 1.0 m; See details in Supporting Report 4-47), with buffer sandwiched between them (see Table 4.4-8 for specifications of bentonite buffer).

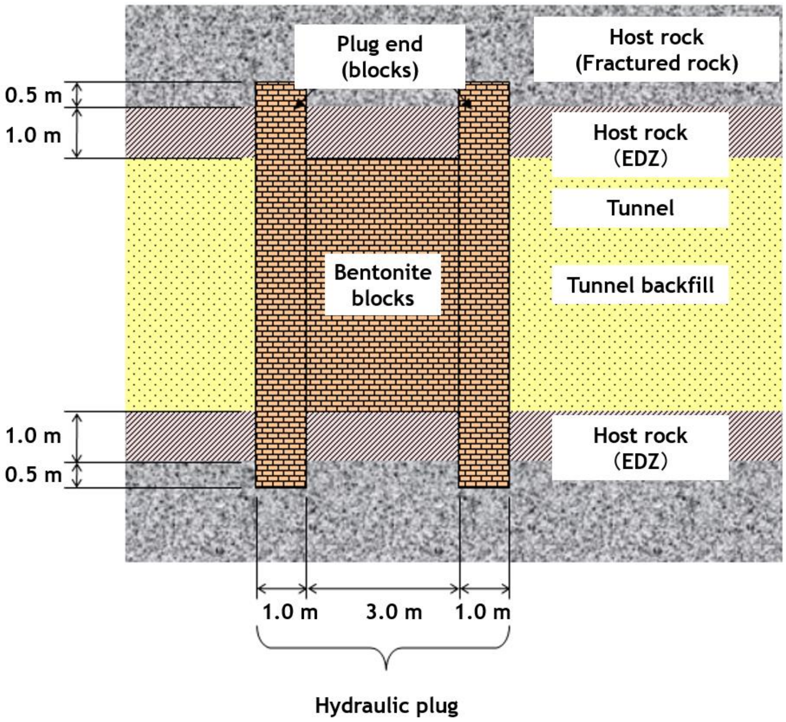


Figure 4.5-14 Structure and dimensions of the hydraulic plug

The notch depth of the ends of the hydraulic plug into the bedrock is set to 1.5 m (EDZ + 0.5 m) for the assumed case in Figure 4.5-14, based on groundwater flow analysis with bentonite permeability coefficient and notch depth as variables. These depths may need to be modified for actual sites, depending on their mechanical properties. In addition, the width of the plug is set such that the permeability of the entire plug is less than that of the host rock before excavation. From the groundwater flow analysis for plutonic rocks (highest hydraulic conductivity of the three rock types), this width was set to 3.0 m. As a result, the total length of the hydraulic plug is 5.0 m. The details on design and the related groundwater flow analyses are given in Supporting Report 4-47.

4.5.4 Design of the underground facility layout

Section 4.5.1 (2) outlined the principles of design of the repository layout based on the SDMs developed in Section 3.3.3 (4) (ii). To simplify the demonstration of the process, the reference repository depths derived in Section 4.3 are taken as fixed although, for specific sites, options for depth optimisation would be considered. Firstly, therefore, based on the spatial distribution of major geologic structures and groundwater flow characteristics at the disposal depth, preferred areas for locating underground facilities are identified. Next, disposal panels are laid out in such areas, to assure that they are of sufficient size and suitable geometry. For a provisional layout of disposal panels, required access and transportation routes will be arranged so that construction and operation can be performed efficiently and safely with appropriate zoning to separate radiation-controlled and non-controlled areas. The tunnel network will be refined to ensure work and material flows can be managed and access to/from the surface provided as required for services such as power, ventilation and drainage. Finally, based on estimates of the percentage of preferred areas where waste emplacement will be difficult (e.g. due to higher water inflow), the layout is checked to ensure that it is possible to find sufficient reserve sections so that the target inventory can be managed.

In the following, this design concept is illustrated for the 3 representative host rocks.

(1) Identifying preferred areas

(i) Design requirements

Table 4.5-13 presents design requirements for preferred disposal areas. In terms of the safety functions and repository components discussed in Section 4.2.4, no relevant safety function is directly applicable to preferred areas, so these are chosen to meet the post-closure safety function of the geological environment (Tables 4.2-4 and 4.2-5) in restricting migration of RNs.

Table 4.5-13 Design requirements for preferred disposal areas

Design requirements	Classification*	Detailed description of requirements for concepts assessed	Specifications
Ease of excavation	-	Conditions suitable for excavation of tunnels	Setting of preferred disposal areas
Reduce the amount of water inflow	-	The amount of drainage during construction and operation is as small as possible	Setting of preferred disposal areas
Restrict migration of RNs after closure	-	Relatively long travel paths in the host rock and low groundwater flux (giving a relatively long transport time)	Setting of preferred disposal areas

* ○: Mandatory requirement, -: preferred requirement (see Section 4.1.2)

In addition, it is necessary to excavate many long disposal tunnels for HLW and hence, from the viewpoints of engineering practicality, safety and also cost of countermeasures (treating drainage water, grouting etc.), design requirements for low water inflow and ease of excavation are included.

Key geological characteristics that need to be considered for these design requirements are the layout determining features (LDFs) that bound the preferable areas (see discussion in Supporting Report 4-48), as noted in Table 4.5-14. Although LDFs may include folds, lithological discontinuities, etc., the focus here is on the major faults that are encountered in all host rocks in Japan. For example, as known from past tunnel construction, excavation through such faults often causes perturbations such as rock bursts or flooding [105], which should be avoided to the extent possible. The width of the damaged zone affecting tunnel construction is assumed to be within 1% of the fault length (see Supporting Report 3-35), and this should be also included as part of the LDFs.

Table 4.5-14 Design requirements related to LDFs

Design requirements	Risks to consider	Geological characteristics of LDFs to consider
Ease of excavation	Mechanical collapse of the tunnel	Mechanical properties
	Flooding	Hydrogeological properties
Reduce the amount of water inflow	Increase in drainage volume during operation	Hydrogeological properties
Restrict migration of RNs after closure	Migration of RNs by fast groundwater flow	Hydrogeological properties. Bedrock permeability, groundwater travel distance

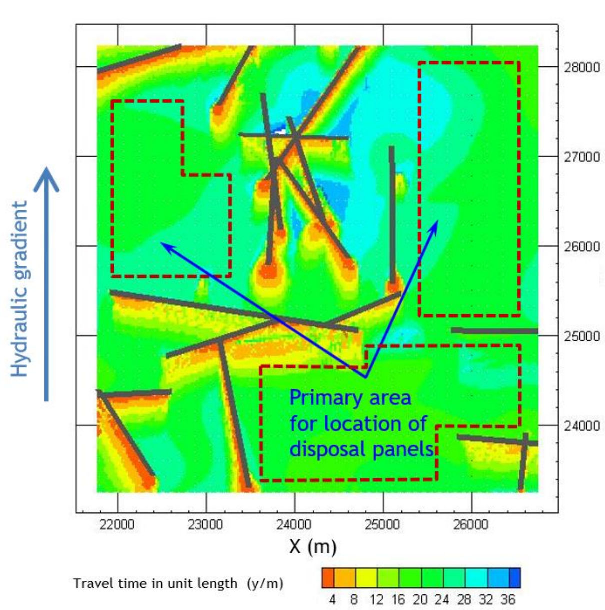
In addition, high water inflow into excavated tunnels presents problems from the viewpoint of drainage water management [105]. In terms of migration of RNs, LDFs may serve as preferential flow paths towards the surface and their impact depends on both the hydrogeological characteristics of the LDF and flow paths through the host rock to them. Thus, LDF characteristics need to be assessed in terms of these three design requirements, with particular consideration of the extent of rock influenced by the presence of the LDF and the degree to which the LDF impacts release and transport of RNs from disposed waste (see Supporting Report 3-35 for further details). In addition, as there is likely to be uncertainty in the position of the fault, it was decided that tunnel emplacement within a few 10s m of the current fault boundary (taking into account associated damaged zone) should be avoided. At actual sites, the characteristics of the LDF at repository depth need to be assessed, as the assumption of preferential flow paths to the surface is inconsistent with general evidence of very old deep groundwater.

(ii) Concept of design within preferable areas

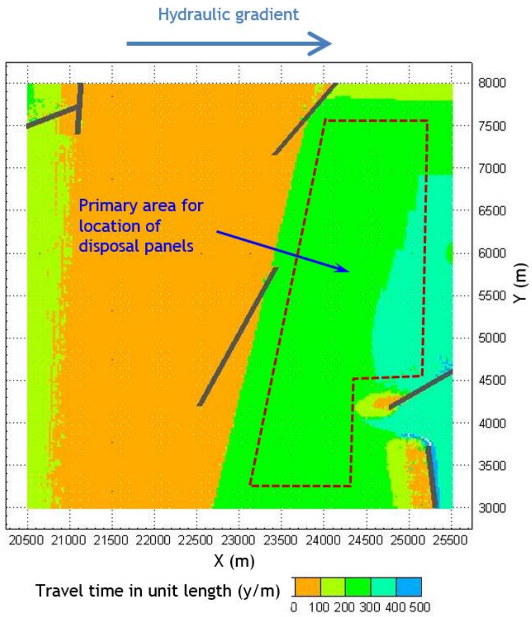
In the design of the underground layout, the 3 SDMs from Section 3.3.3 (4) (ii) are used (Figures 3.3-29, 3.3-35 and 3.3-41). From these SDMs, maps of preferred areas at repository depth are developed based on the conservative assumption that all LDFs are potential preferential flow paths, as illustrated in Figure 4.5-15. A very simple measure of “relative travel time” of groundwater through the host rock was calculated based on the specific distance from a targeted point in a host rock divided by the modelled Darcy velocity. The specific distance was tentatively determined to be 500 m based on the scoping calculations. More information on the calculation these relative travel times is given in Supporting Report 4-49.

For plutonic rocks, Figure 4.5-15 (a), groundwater flow is driven by the hydraulic gradient and the relative travel times tend to be short up-gradient from LDFs. Therefore, the mapped preferable areas are larger blocks that avoid such zones.

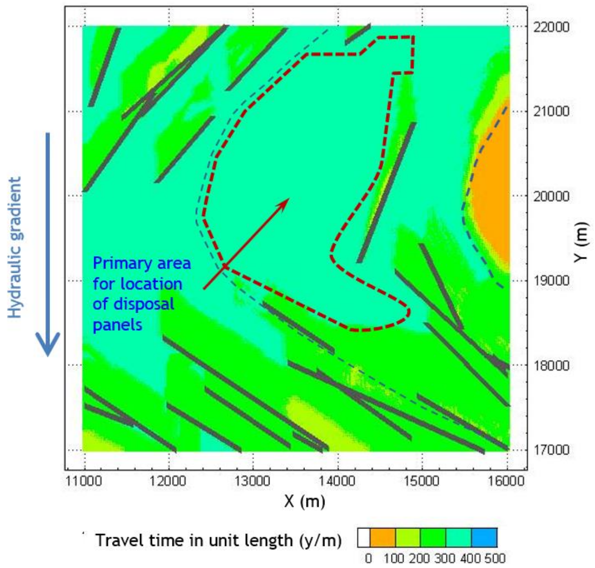
For Neogene sediments, Figure 4.5-15 (b) can be compared to the repository-scale geological SDM (Figure 3.3-34); it is then clear that both sandstone layers and faults tend to have higher permeability, giving short relative travel times. The preferable areas thus lie in the lower conductivity mudstone layer. Similarly, for Pre-Neogene sediments, Figure 4.5-15 (c) and can be compared with Figure 3.3-40 (left); relative travel times tend to be short near both faults and chert blocks. Since the permeability is equally low in mudstone-dominant and sandstone-dominant matrices, it was decided to prioritise the mudstone-dominant matrix as it is present over a larger area.



(a) Plutonic rock (1,000 m below surface)



(b) Neogene sediment (500 m below surface)



(c) Pre-Neogene sediment (1,000 m below surface)

Figure 4.5-15 Distribution of relative travel times and selection of preferable areas

(2) Setting of disposal panel shape

The shape of disposal panels (groups of disposal tunnels and the tunnels connecting them) is set following consideration of construction and operational methods.

(i) Design requirements

Design requirements considered to set disposal panel shape are captured in Table 4.5-15. Here, main issues related to engineering practicality (see Table 4.1-1) are captured in terms of operational practicality, disposal volume and ventilation air speed.

Table 4.5-15 Design requirements on disposal panel shape

Design requirements	Classification*	Detailed description of requirements valid for concepts assessed	Specifications
Panel shape facilitates operations	○	Ensure minimum turning radius of equipment is allowed for	Tunnel junction angles Junction area widening
Disposal volume	○	Able to dispose of specified waste inventory	Number and length of disposal tunnels
Ventilation air speed limit	○	Air speed in all tunnels is below the specified limits	Ventilation plan/requirements Number of disposal tunnels ventilated

*○: Mandatory requirement, -: preferred requirement (see Section 4.1.2)

(ii) Issues associated with disposal panels

Different disposal panel configurations are being considered in countries planning geological disposal, as discussed further below.

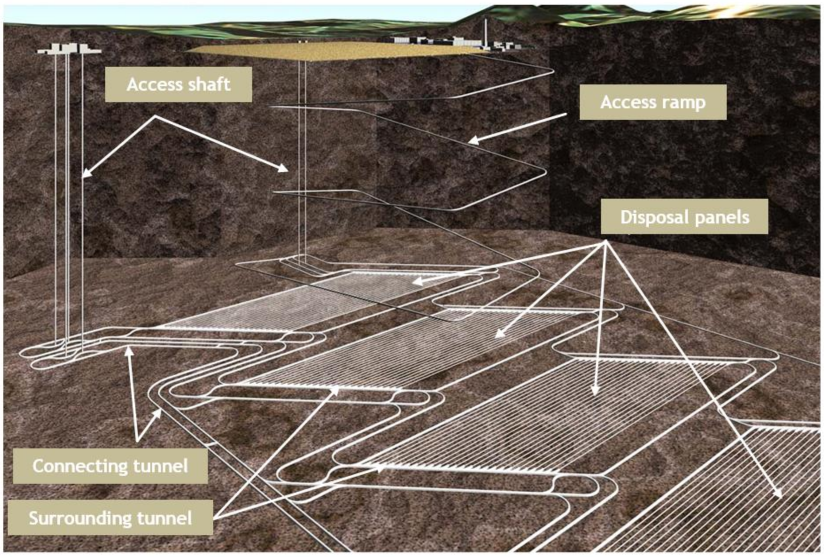
(a) Through and dead-end tunnels

For HLW disposal, two fundamental design options involve either parallel groupings of through tunnels (TTs: accessible from both ends, Figure 4.5-16 (a)) or dead-end tunnels (DETs: accessible from only one end, Figure 4.5-16 (b)).

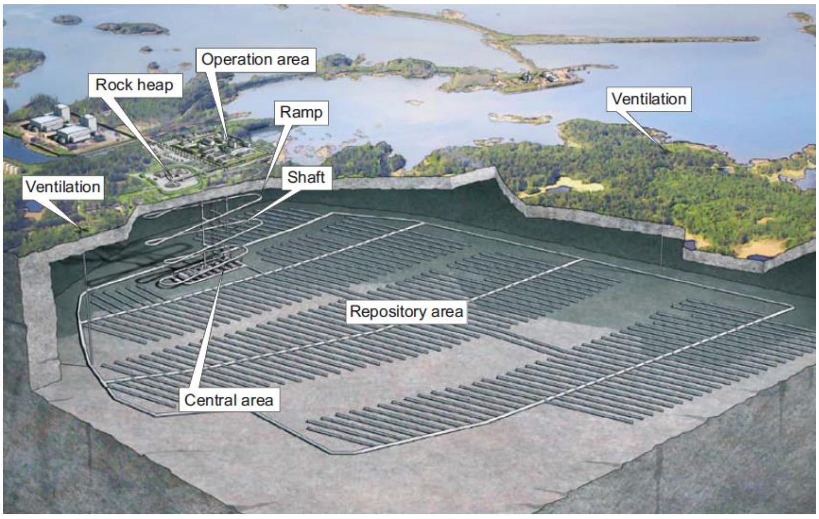
TT layouts have been continuously studied in Japan since H12. Because they are accessible from both ends, this may have some advantages in terms of work flow during construction and operation [6]. Additionally, the surrounding tunnel provides additional characterisation information to reduce the risk of surprises during emplacement tunnel excavation. Such panels were also previously examined in Switzerland (for crystalline [106] and sedimentary [107] host rocks).

Use of DETs allows the length of each to be tailored to the preferable rock area available and avoids the need for a surrounding tunnel. Such flexibility is particularly important when the rock structure is complicated but can be well characterised from the surface, e.g. in countries such as Finland [108], Sweden [109] and recently in Switzerland [110], or those considering alternative disposal options (in horizontal boreholes, France [111] or caverns Canada [112]). It is also worth noting here that dead-end tunnels are of particular benefit if they can be laid out in a way that reduces the risk of access routes acting as preferential flow paths. The disposal panel concept and shape for HLW and TRU waste has to be tailored to the preferred disposal areas indicated in Figure 4.5-16.

For H12V, both through and dead-end tunnels were considered [6], [109]. As described in Section 2.3.4, the H12 repository concept was the starting point for design and hence, for H12V, TT as in H12 are prioritised. However, given that H12V is already rather inefficient in terms of use of space [6], the additional requirements for the surrounding tunnel may cause this option to be re-assessed for sites where available repository footprints are restricted.



(a) Through tunnels (TT)



(b) Dead-end tunnels (DET)

Figure 4.5-16 layout example of underground facilities (Source: (a) NUMO, 2011 [1], (b) SKB, 2010 [108])

For the PEM case, the logistics of tunnel construction/waste emplacement are simpler than H12V, so TT may have fewer advantages. Further, similar disposal concepts (SKB KBS-3H [14] and the Belgian super container [113]) are based on dead-end tunnels, so these are also considered here.

For TRU waste, the disposal footprint is relatively small and hence TT as in TRU-2 are taken as a reference. The disposal vaults involved use a large amount of concrete and mortar for construction of the structural body, infill, etc., so the length of such vaults is constrained by practical concrete pumping distances. For waste groups with small volume, however, DET options could be much more cost-effective.

(b) Disposal tunnel junctions with the connecting tunnel

The crossing angle between disposal tunnels and the connecting tunnel has been designed in consideration of the minimum turning radius of the type of equipment required to pass through the junction. In general, orthogonal junctions are favourable from the viewpoint of mechanical stability (see Supporting Report 4-50).

As described in Section 4.4.3 (1) (i), the H12V concept is based on H12, which considered TT and rail transportation of waste underground. This was the starting point for design and technical development of the EBS emplacement device. In this case, the junction between the connecting tunnel and the disposal tunnel is a curve set by the practical limits on rail transport, resulting in a panel with a parallelogram shape (see Figure 4.5-17 and Supporting Report 4-50).

For the PEM, road transportation was considered, which allows a smaller turning radius and the option of widening access to the disposal tunnel to provide space to turn in from an orthogonal tunnel junction. In addition, the option of dead-end disposal tunnels is considered, with dead-end tunnels/road transport also being considered for H12V in the future.

For TRU waste, as mentioned in Section 4.4.3 (2), road transport is assumed and, to assure mechanical stability, an orthogonal junction between the connecting tunnel and the disposal vault is assumed.

(c) Number of disposal panels

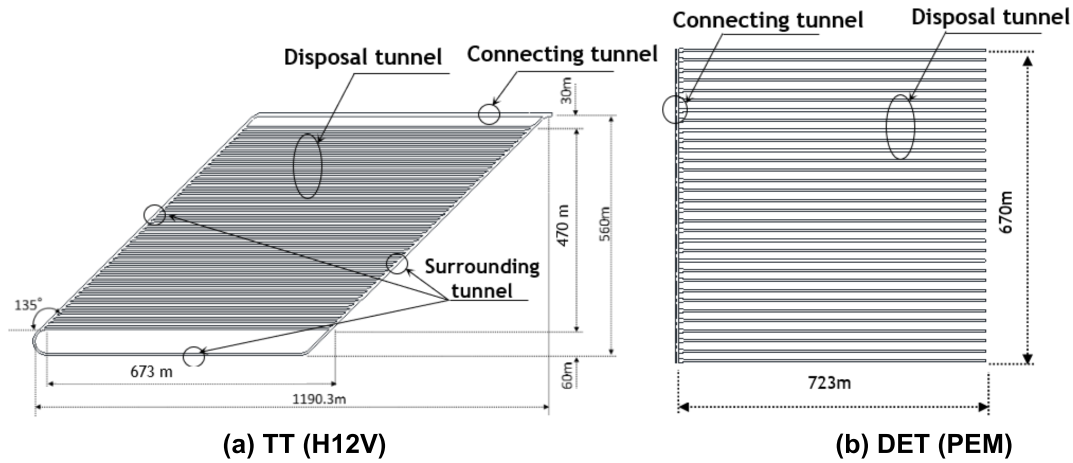
For HLW, following definition of the shape of disposal panels, the number of these is set by considering excavation and operational work flows (for these running in parallel) and practical aspects such as ventilation wind speed. This results in between 6 and 8 panels, which are currently assumed to contain the same quantity of HLW, although this could be further optimised on a site-specific basis. Details of the setting of the number of HLW disposal panels are shown in Supporting Report 4-51.

In the case of TRU waste, the entire repository is treated as one panel, although separated into different areas for the different TRU waste groups.

(iii) Specification of disposal panel options

(a) HLW

Examples of panel concepts for H12V and PEM are illustrated in Figure 4.5-17.



(a) TT (H12V) **(b) DET (PEM)**

Figure 4.5-17 HLW disposal panel shape and dimensions (plutonic rock)

The details of the designs and associated analysis are given in Supporting Report 4-52 for the 3 SDMs, the results of which are summarised in Table 4.5-16. For H12V in the case of plutonic rock and Neogene sediments, parallelogram-shape TT panels are selected as a reference (Section 4.5.4 (2) (ii) (a)). The disposal tunnel access radius of curvature, is set to 30 m [114] and the pitch between disposal tunnels is as set in Section 4.5.2 (3) (iii). Although certainly a parameter that would be considered further for site-specific boundary conditions, the number of panels was set to 6 and the length and number of disposal tunnels then determined.

Table 4.5-16 HLW disposal panel options

Disposal concept	Plutonic rock	Neogene sediments	Pre-Neogene sediments
H12V	TT: 6 panels	TT: 6 panels	DET: 8 panels
PEM	DET: 6 panels	DET: 6 panels	DET: 8 panels

For Pre-Neogene sediments, the SDM is more complex and DET panels were selected (8 in this case) in order to provide flexibility to make best use of preferable areas. For the PEM, DET panels are chosen for all SDMs (Section 4.5.4 (2) (ii) (a)), with tunnel pitches as derived in Section 4.5.2 (3) (iii).

(b) TRU waste

The TRU waste disposal area treated as 1 panel (Section 4.5.4 (2) (ii) (a)), with vault lengths set on the basis of practical concrete pumping distances. Although pumping distances have been reported that exceed 1,000 m, in order to assure quality, $< \approx 300$ m is considered to be a general limit [115]. With further consideration of limited clearances, remote operation under radiation-controlled conditions, etc., additional conservatism leads to a limit for concrete pumping to be set at about 200 m, which may be re-assessed during later optimisation, especially as it may be practical to pump concrete from either end of the vault. However, the complexity of TRU waste means that a very large range of processes impact their evolution with time. The current assessment is illustrative only and focuses on relatively well-defined impacts. However the current analysis will form the basis for more comprehensive analyses in the future that include additional processes such as gas release/transport and effects of microbes.

The layout of vaults was set in consideration of the following:

- Wastes containing RNs that have high solubility and low sorption, especially I-129 and C-14 (Gr.1 and Gr.2), are positioned upstream from other groups, so that groundwater transport distances will be maximised assuming no future changes in flow directions.
- Gr.3 wastes, containing nitrate, are located to minimise potential effects of leached nitrates on other waste groups, and hence off the flow path/upstream side of all other groups.
- Wastes with higher thermal output (Gr.2 and Gr.4H) are placed as far towards the edges of the disposal panel as possible.
- The impact of heat generated is minimised by alternating vaults containing higher and lower thermal output waste.

The general arrangement of vaults based on these considerations is shown in Figure 4.5-18.

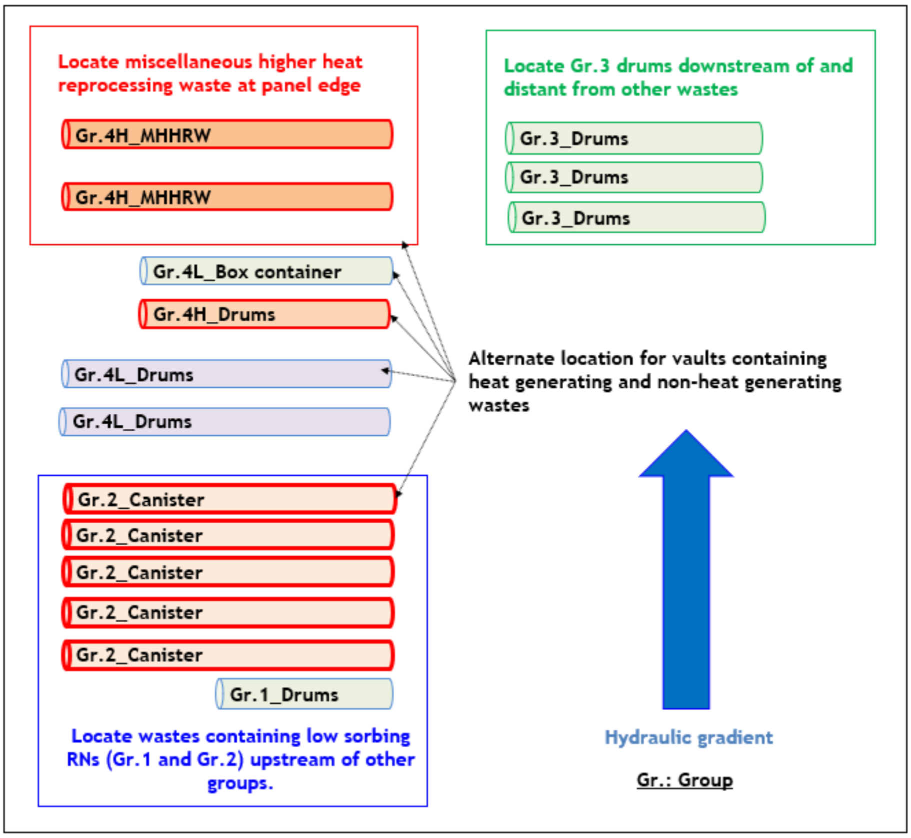
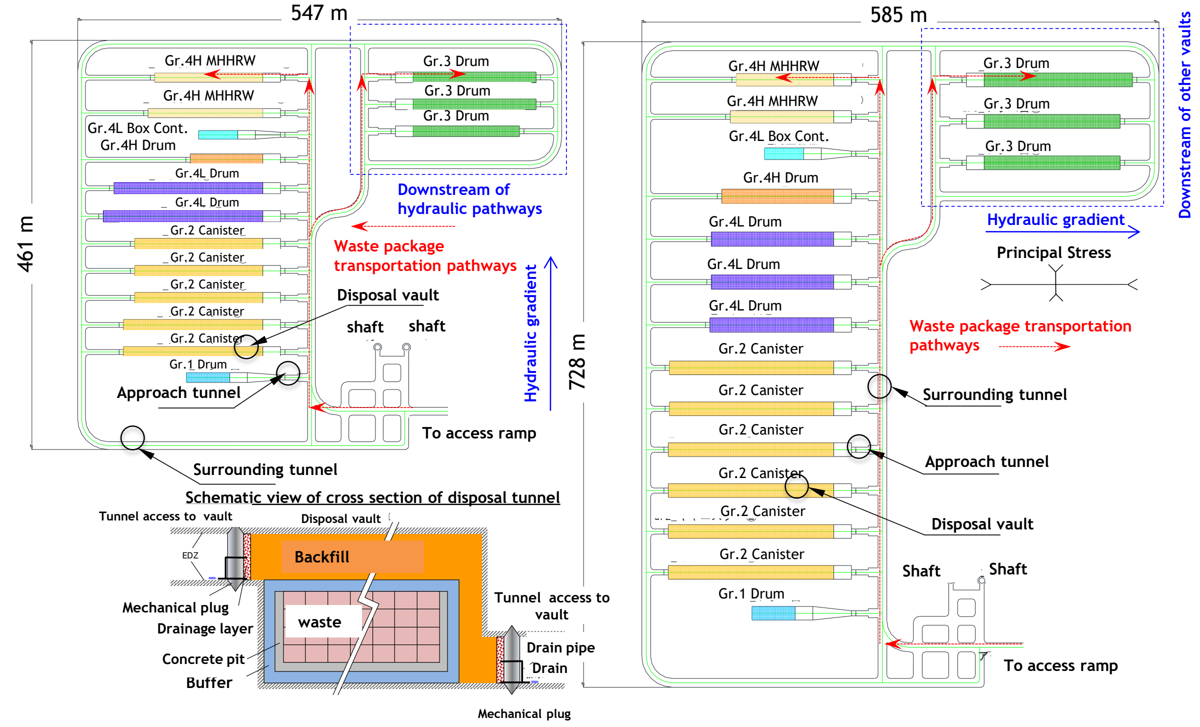


Figure 4.5-18 Constraints on location of TRU vaults (container for MHHRW not yet specified)

Resultant TRU waste disposal panel layouts are shown in Figure 4.5-19 (based on an assessment described in Supporting Report 4-42).



(a) Plutonic rock and Pre-Neogene sediment **(b) Neogene sediment**

Figure 4.5-19 TRU waste disposal vault layouts

Compared to plutonic rocks and Pre-Neogene sediments, the larger disposal area for the Neogene sediments results from its lower strength, requiring larger vault spacing to assure mechanical stability. As mentioned above, Grs.1 and 2 are upstream and Grs.4L and 4H alternate to spread thermal load. Gr.3 was placed away from all other groups at the downstream end of the panel.

The surrounding tunnels run around the parallel disposal vaults, with waste input from the same end of each. Further, as mentioned in Section 4.5.4 (2) (ii) (b), waste package transport is assumed to be road based and the junction of the vault with the surrounding tunnel is a right angle. The link from the surrounding tunnel transporting waste to the vault is level with the vault floor, while the opposite surrounding tunnel is at roof level (see Figure 4.5-12 (b) or Figure 4.5-19 inset), with more details in Supporting Report 4-53. It should also be noted here, that there are some DET, specifically for Gr.1 and some Gr.4L waste. This illustrative design is based on safety and efficiency considerations for construction of such a relatively large cross-sectional area vault.

(3) Arrangement of disposal panels

Figure 4.5-15 shows the preferred locations for disposal in the different SDMs (outlined in Section 4.5.4 (2) (iii)), which are now considered in more detail.

(i) Design requirements

The design requirements for laying out disposal panels are given in Table 4.5-17, based on pre- and post-closure safety functions for repository components from Section 4.2.4 (Table 4.2-3 and Tables 4.2-4 and 4.2-5, respectively).

Table 4.5-17 Design requirements for panel layout

Design requirement	Classification*	Detailed description of requirements for concepts assessed	Specifications
Restricting groundwater flow along the disposal tunnel	-	The direction of the disposal tunnel is orthogonal to the current hydraulic gradient	Orientation of disposal tunnels
Assuring stability of the disposal tunnel	-	The direction of the maximum principal stress and orientation of the tunnels are optimal	Orientation of disposal tunnels, specifications of tunnels (support etc.)
Managing groundwater drainage	-	The slope of the disposal tunnel and that of the panel overall should be set so that water draining from radiation control areas will not move to other disposal areas. Manage drainage by gravity flow to the extent possible	Slope of disposal tunnels and surrounding/connecting tunnels, Sump volumes and locations
Reduction of waste interactions in case of co-disposal	○	In the case of co-disposal, arrange the disposal sections so that the HLW and TRU disposal sections do not interact thermally or chemically.	Arrangement of panels for HLW and TRU

* ○: Mandatory requirement, -: preferred requirement (see Section 4.1.2)

Requirements include restricting groundwater flow along the disposal tunnels and assuring stability of the disposal tunnel, which impact the location and orientation of the disposal panel. Also, the requirement for engineering practicality leads to arrangement of tunnel slopes so that gravity provides required drainage. Although forced drainage by pumps is possible, this tends to be more complex and is not failsafe in the event of power loss.

For the case of HLW and TRU waste co-location, interactions due to heat from HLW or chemical plumes from TRU waste (e.g. high pH, organic substances and nitrates) should be kept as low as possible [10] [11] [116]. Therefore, reduction of interactions is set as a design requirement for post closure safety.

(ii) Determination of disposal tunnel orientation

From Table 4.5-17, orientation of tunnels needs to be considered in terms of both mechanical stability and groundwater flow along tunnels. In terms of the former, the orientation of tunnels can be optimised for mechanical stability with respect to the local horizontal stress field. However, it is suggested to be generally preferable that disposal tunnels are orthogonal to the hydraulic gradient, to avoid them acting as preferential flow paths, but additional numerical simulations may be required to assess this. If these requirements conflict, a more detailed analysis is needed to determine how trade-offs lead to an optimal solution.

For the host rocks examined in this report, the Neogene sediments show stress anisotropy with the stress maximum in the same direction as the hydraulic gradient. In this case, the safety of workers requires that stability is given more weighting, as post-closure safety can be shown even with non-optimal groundwater flow conditions (see Section 6.4). For other rock types, the two requirements are compatible and setting tunnel direction is straightforward. The details of determination of the direction of the disposal tunnels for each SDM are given in Supporting Report 4-54.

(iii) Slope of disposal tunnels

The HLW disposal tunnels are excavated with a slope to provide the gradient driving natural gravity drainage during construction and operation. During excavation, work progresses up slope to facilitate such drainage. The approach to drainage during backfilling differs between TT and DET cases (Figure 4.5-20 (a), (b)). In the TT case, where both ends of the disposal tunnel link to connecting tunnels, it is necessary to install a mechanical plug at one end before backfilling commences, so either up-slope or down-slope options are possible. On balance, it was considered advantageous to backfill up-slope if drainage is assured through the mechanical plug (Figure 4.5-20 (a)). For the DET case, the only option is clearly backfilling downslope, reversing the direction of original excavation (Figure 4.5-20 (b)). However, simultaneously balancing all requirements for excavation, drainage, ventilation and backfill installation logistics is tricky, especially for TT tunnels which allow fewer options. More development work here will be needed in future stages of the design work.

Nevertheless, taking the above into consideration, the slope direction was set, with a reference gradient of 1% assumed [98].

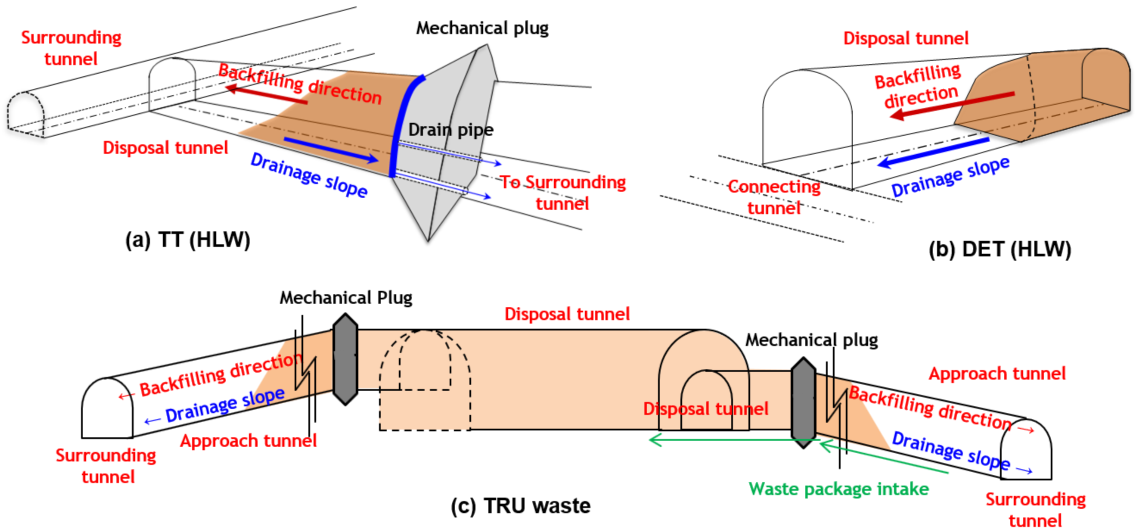


Figure 4.5-20 Tunnel gradients and direction of backfilling

The TRU vaults are currently designed to be horizontal, based on consideration of construction, buffer emplacement, transportation of waste packages by gantry cranes and infilling. A drainage channel with a slight gradient would allow natural flow to the lower approach tunnel during construction and operation. Approach tunnels would slope down from the disposal vault towards the connecting tunnel, providing drainage while these are backfilled (Figure 4.5-20 (c)).

(iv) Arrangement of panels for co-disposal

To reduce chemical and thermal interactions between disposal panels for HLW and TRU waste, these are separated by as much distance as required, with TRU waste down hydraulic gradient from HLW [116]. This leads to an outline layout that is evaluated in the post-closure safety assessment (see Section 6.4), allowing it to be modified if any issues are identified.

(4) Arrangement of connecting and access tunnels

After arranging the disposal panels, the necessary connecting and access tunnels (ramps and shafts) can be laid out so that work and material flows for construction and operation, together with service routes for ventilation and drainage, are provided in an optimal manner. In addition, provisions for transferring HLW overpacks/PEMs need to be arranged at the junction of access and connecting tunnels.

(i) Design requirements

Table 4.5-18 shows the design requirements for layout of access and connecting tunnels. For such tunnels, requirements relate to operational safety and engineering practicality, as set in Table 4.5-2.

Because of planned parallel construction and operation (for HLW), zoning of underground areas is essential and thus independent work flow routes (material and manpower), ventilation and drainage are required for radiation-controlled (access restricted to nuclear workers) and non-controlled zones (construction worker access). For each zone, practicality of construction (mechanical stability) and operation (limiting ramp gradients) needs to be complemented with appropriate measures for responding to relevant perturbations (e.g. assuring escape routes).

Table 4.5-18 Design requirements for layout of access and connecting tunnels

Design requirement	Classification*	Detailed description of requirements for concepts assessed	Specifications
Ensuring independence of work flow lines	○	Work flow lines for construction materials, equipment and spoil, are independent and do not intersect those for waste emplacement and backfilling	Number and layout of tunnels and their relationship to access routes (ramp/shaft)
Ensure independent ventilation	○	Appropriate ventilation routes are assured, which are independent in the radiation-controlled and non-controlled zones	Placement of tunnels, Separation of air intake and exhaust routes, placement and number of access routes
Ensure independent drainage	○	Appropriate drainage routes are assured, which are independent in the radiation-controlled and non-controlled zones	Arrangement and slopes of contact tunnels, location and volume of sumps
Securing evacuation routes	○	In case of credible accidents, appropriate escape routes are assured and, in case these cannot be accessed, suitable emergency shelters are provided	Evacuation routes, emergency shelters
Access slope limit	○	Set gradient within limits for the transportation method used	Access ramp slope
Ensuring mechanical stability of tunnels	○	Mechanical stability is assured in all tunnels	Pitch between connecting tunnels, management of traverses through major structural features

*○: Mandatory requirement, -: Preferred requirement (see Section 4.1.2)

The arrangement of connecting and access tunnels depends on the specific layout of disposal panels, as outlined in Section 4.5.4 (2) (iii), and varies significantly for HLW and TRU waste, as the latter does not involve parallel construction and operation. Since the panel layouts are tailored to each SDM, final design can be developed only after such tailoring (Section 4.5.4 (6)). The following thus establishes only the basic design principles and constraints and does not include implementation practicalities (e.g. re-zoning after completion of excavation of a panel).

(ii) Layout of connecting and access tunnels

(a) HLW TT panels

A conceptual sketch of tunnel layout for HLW TT panels is shown in Figure 4.5-21, highlighting the main features to allow parallel construction and operation. It should be emphasised that the work flows are illustrative only and would be specified on the basis of site-specific repository layout, along with required procedures for re-zoning panels after construction is complete.

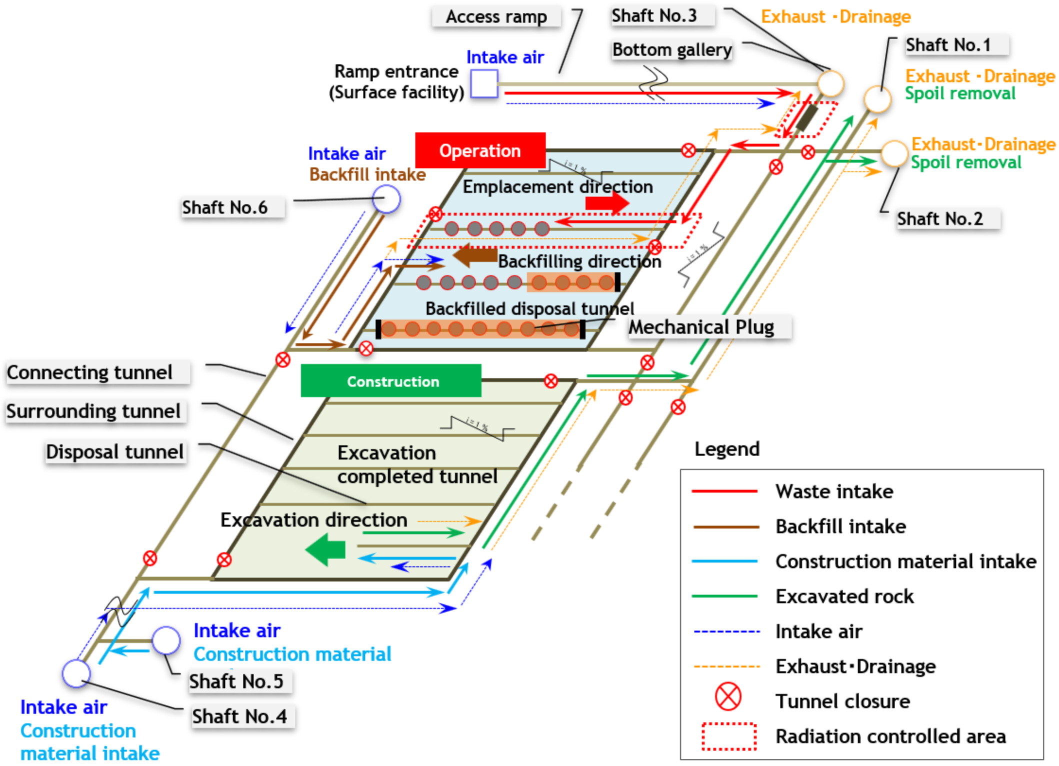


Figure 4.5-21 Conceptual sketch of tunnel layout (HLW TT panels)

The associated sequence for construction and operation of 6 disposal panels is given in Figure 4.5-22.

Emplacement panel	Timeline							
Connecting tunnel Surrounding tunnel	Excavation		Transport･Ventilation ･Drainage					
Emplacement panel ①		Construction	Operation					
Emplacement panel ②			Construction	Operation				
Emplacement panel ③				Construction	Operation			
Emplacement panel ④					Construction	Operation		
Emplacement panel ⑤						Construction	Operation	
Emplacement panel ⑥							Construction	Operation

Figure 4.5-22 Sequence of construction and operation of panels (HLW 6 TT panels)

After construction of the first disposal panel, construction and operation are carried out in parallel, requiring appropriate zoning. Independent routes are provided for intake of construction materials and removal of excavated spoil as shown in Figure 4.5-21, separating panel (2) access and connecting tunnels from those used to dispose of waste in panel (1).

There are also separate ventilation circuits and drainage routes, with any required bulkheads or tunnel plugs to prevent interaction between the 2 zones (see Supporting Report 4-60 for details).

Within the operating panel, material flow routes are established to allow waste emplacement and backfilling/sealing of filled tunnels to run in parallel, which may be important for the more complex emplacement/backfilling operations for the H12V case. As previously discussed, relevant connecting tunnels are dimensioned to handle 2-way traffic (see Table 4.5-6) and parallel connecting tunnels, with bulkhead doors to allow changing connections, can be planned to facilitate re-zoning.

As shown in Figure 4.5-17 (a), the TT panel allows access of large equipment only in pre-determined directions. Nevertheless, the complicated process of emplacing the H12V overpack and associated buffer and then backfilling can be efficiently managed if these utilise access to the disposal tunnel from different directions (backfill shown as brown and overpacks in filled circles in the upper (operational) panel of Figure 4.5-21).

Ventilation and drainage routes are established to limit impacts of possible operational perturbations, for example ensuring that the exhaust from the disposal tunnel in which HLW is being emplaced does not flow into tunnels being backfilled. The air intake follows the backfill transport, while exhausts follow the route of the waste emplacement equipment. Although manual backfilling is currently assumed, remote handling of this operation could both reduce ventilation constraints and simplify control of worker access to areas containing waste.

Tunnel slopes are set so that drainage from the panel under construction and that under operation could be collected independently in sumps below separate “active” and “inactive” drainage shafts. As a result of this layout, there are sections where connection tunnels run in parallel, so an appropriate pitch is set to ensure mechanical stability.

Based on the above study, the required number and roles of access routes can be defined, as shown in Table 4.5-19.

Table 4.5-19 Access roles (H12V TT panels)

No.	Name	Function	Role of ventilation
Ramp	Operational ramp	Overpack and buffer transportation	Air intake
Shaft No. 1	Spoil removal shaft 1	Spoil removal, drainage (inactive)	Exhaust (inactive)
Shaft No. 2	Spoil removal shaft 2	Spoil removal, drainage (inactive)	Exhaust (inactive)
Shaft No. 3	Ventilation shaft	Drainage (active)	Exhaust (active)
Shaft No. 4	Materials and Equipment Shaft 1	Construction materials, personnel, equipment	Air intake
Shaft No. 5	Materials and Equipment Shaft 2	Construction materials, personnel, equipment	Air intake
Shaft No. 6	Materials and Equipment Shaft 3	Backfill materials, personnel, equipment	Air intake

The ramp provides a transport route for the overpack and buffer and, together with shaft 6 (backfill support shaft), also acts as an air intake for radiation-controlled zones. Active exhaust and drainage are provided by shaft 3. Shafts 4 and 5 support construction operations and provide air intake for construction zones, with inactive exhaust and drainage provided by spoil removal shafts 1 and 2. It should be noted here however, that designs will need to be adapted to site conditions and therefore further studies would optimise use of access routes.

In terms of emergency evacuation routes, air exhaust shafts (No. 1 to 3) would not be used as these may be smoke-filled in the event of a fire. Hence, independent routes would be provided to shafts 4 to 6, potentially with the option of escape via bulkhead doors between shaft 4/5 and 6, which would otherwise be kept closed to isolate these zones. In case of accidents when evacuation routes cannot be accessed, emergency shelters will be set up, but number, locations and design of these will be considered only in the future.

(b) HLW DET panels

A conceptual sketch of tunnel layout for HLW DET panels to assess access requirements is shown in Figure 4.5-23. Note that, if orientation of disposal tunnels perpendicular to the hydraulic gradient is not practical, all tunnels should be oriented so that dead ends are down-gradient to avoid risks for preferential RN transport along the EDZ.

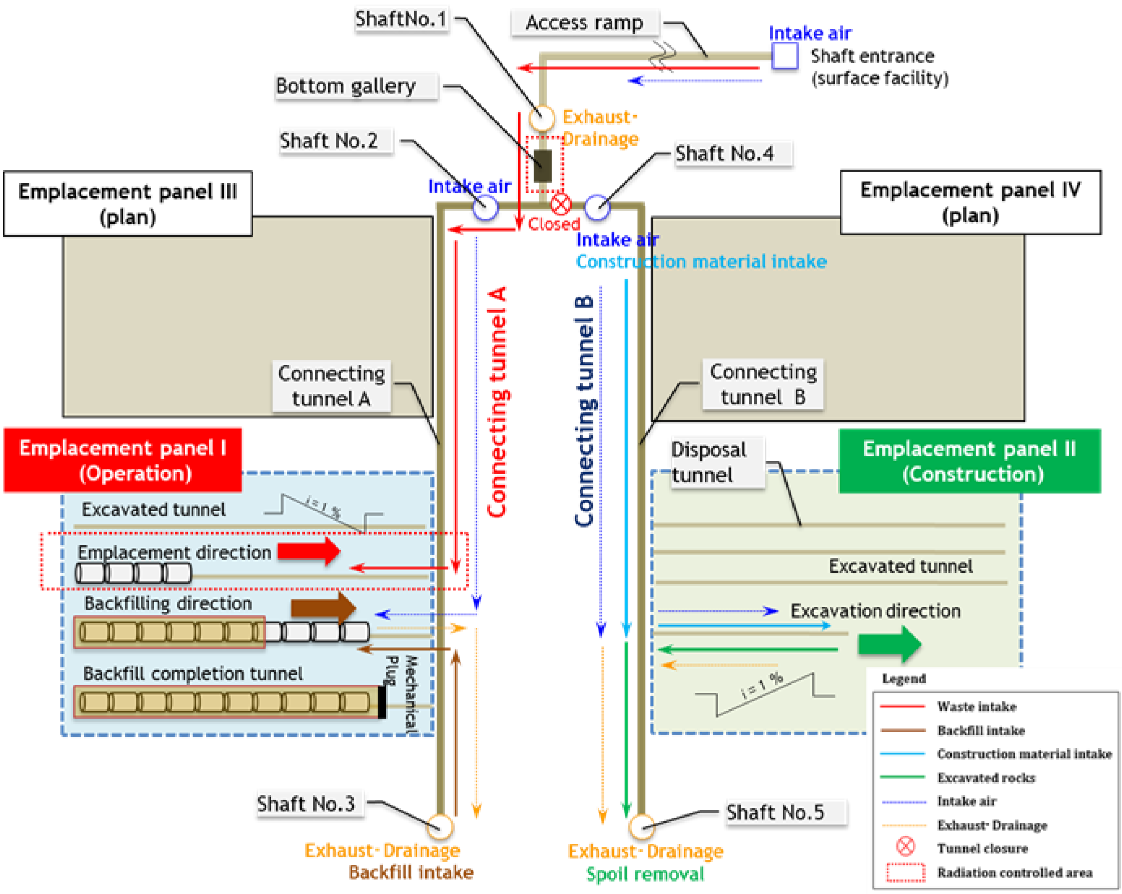


Figure 4.5-23 Conceptual sketch of tunnel layout (HLW DET panels)

It should be emphasised that all considerations of independent ventilation, drainage and escape routes for active and inactive zones are not included and hence parallel connecting tunnels with crossover points closed by bulkhead doors would be incorporated in the final design.

The associated sequence for construction and operation of DET panels is given in Figure 4.5-24.

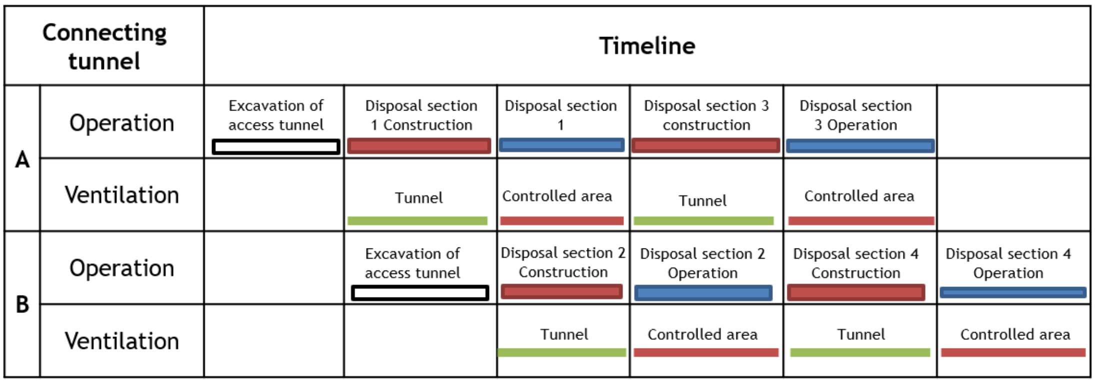


Figure 4.5-24 Sequence of construction and operation of panels (HLW 4 DET option – only conceptual at this stage)

For the PEM option, when all emplacement operations are carried out by tele-operated or automated equipment, backfill transported against the flow of active exhaust air and drainage would not be problematic (although tunnel sealing may also need to be remote handled to completely remove this issue). However, this would require a more complex connecting tunnel layout to provide worker access for H12V manual backfilling, which would presumably require to be via shaft 4. Emergency escape would also require connections between the active and inactive zones and, in case of a fire in the construction panel, a second escape route would inevitably pass through a radiation-controlled zone. Such considerations will form the basis of more detailed assessment of this option.

As for the TT case, tunnel slopes are set so that drainage of the construction and operational panel is independently routed to the inactive and active drainage shafts, respectively. For the sections where connection tunnels run in parallel, an appropriate pitch was set to ensure mechanical stability.

Based on this concept, the roles of access routes are shown in Table 4.5-20, based on 1 ramp which provides a transport route for the overpack and buffer/PEM and also acts as an air intake, and 5 shafts for ventilation, drainage, material transfer, and access by workers. In this option, all ventilation exhaust and drainage from DETs is into a single connecting tunnel so flows are somewhat simpler but, during rezoning, either the functions of shafts 2/3 and 4/5 need to be exchanged or (probably much simpler) alternative connecting tunnel routes are required for the A and B operational sides.

Table 4.5-20 Access roles (H12V/PEM DET panels)

No.	Name	Function	Ventilation role
Ramp	Ramp	Transport of overpack and buffer or PEM	Air intake
Shaft No. 1	Ramp ventilation shaft	Ramp drainage	Exhaust (active)
Shaft No. 2	Materials transport shaft A	Construction, personnel and equipment	Air intake
Shaft No. 3	Spoil removal shaft A	Excavated spoil, backfill materials and drainage	Exhaust (active)
Shaft No. 4	Materials transport shaft B	Construction, personnel and equipment	Air intake
Shaft No. 5	Spoil removal shaft B	Excavated spoil, backfill materials and drainage	Exhaust (inactive)

As the background provided by H12 for TT is not available for the DET option, the assessment is currently at a much simpler conceptual level, which will be refined in the future on the basis of issues identified.

(c) TRU waste

TRU waste disposal operations occur within a single panel (see Figure 4.5-19) after all excavation and construction has been completed and hence there are no zoning issues here (N.B. that this assumes the inventory is not modified after initial construction). Waste packages are transported underground by the dedicated ramp, while infilling/backfilling material is transported via shafts.

As described in Section 4.4.3 (2), waste packages are transported from the surface to the disposal vaults directly, without any trans-shipment between ramp and underground transporters. When emplacing with a remote-controlled forklift, packages are carried directly from the transporter to the emplacement cell using established technology. When emplacing with a gantry crane (see Figure 4.4-30), waste packages are lifted directly from the transport vehicle to their disposal location within the operational disposal cell by remote control. It is currently assumed that waste transportation and backfilling/sealing vaults will be manual, hence defining ventilation and emergency escape requirements, but remote handling here may be an option in the future.

Drainage water will flow down the gradient of the tunnel floor in the TT and will be collected at a sump located at the lowest point and pumped up the associated shaft.

(iii) Design of trans-shipment chamber

The access ramp reference design has a square-spiral structure, allowing a relatively gentle slope (for road transport) without an excessive footprint, but other designs (or rail transport) may be considered in the future. Straight sections are 1,000 m long and each 90° corner has a radius of curvature of 30 m. In addition, the slope was set to 10%, based on precedents in other countries [117] [118].

For H12V, overpack and buffer are transferred at the bottom of the ramp to rail transport vehicles for emplacement, as shown in Figure 4.5-25.

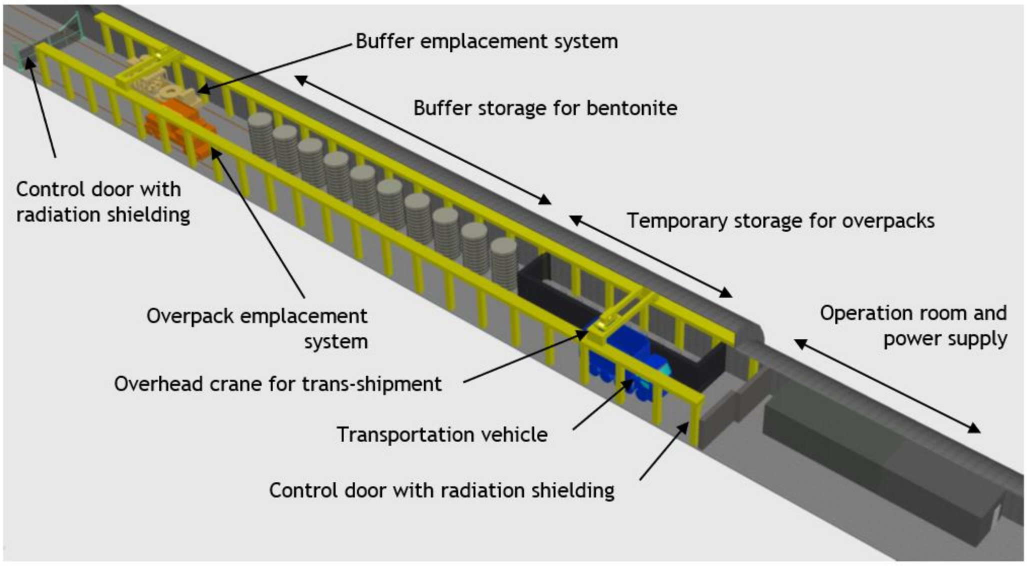


Figure 4.5-25 Layout at bottom of trans-shipment chamber (H12V)

At this location, a shielded temporary store for overpacks and buffer serves to smooth operational logistics. Transhipment and other movements are carried out using a remote-controlled overhead crane and thus the height of the tunnel here is higher than that of either the connecting tunnel or access ramp.

For the PEM case, at the bottom of the ramp the road transporter can directly transfer the PEM to the rail-based transport and emplacement machine, as shown in Figure 4.5-26.

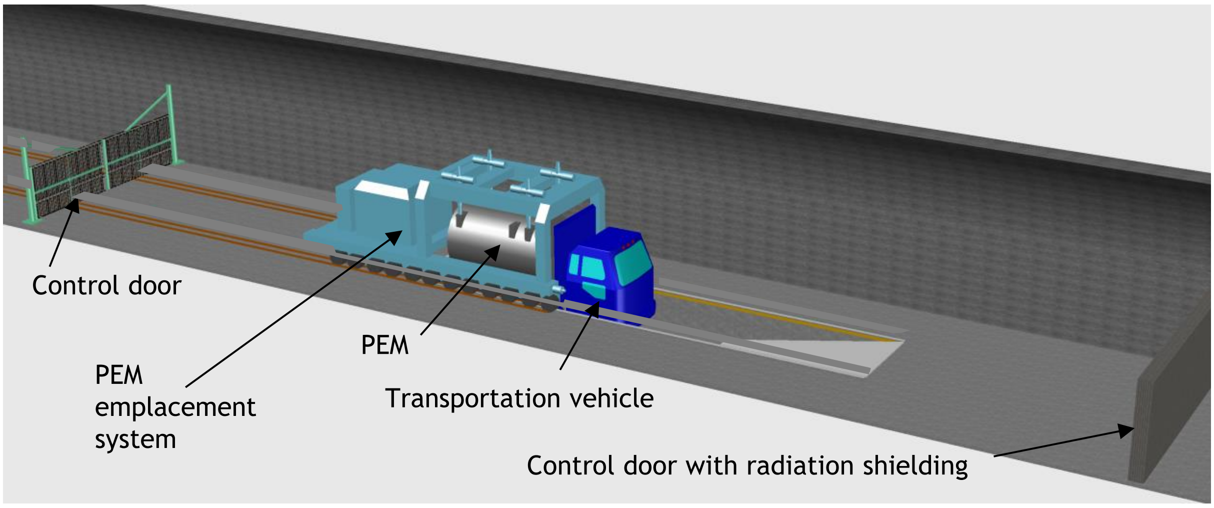


Figure 4.5-26 Layout at bottom of trans-shipment chamber (PEM)

Further logistical analyses will be carried out in the future to assess whether temporary stores for PEMs will be needed (e.g. when decisions are made on where the PEM (and buffer components) will be manufactured and when site conditions/restrictions are better known). This assumes that the emplacement machine can lift the PEM directly from the bed of the transport vehicle with a gripping device having a twist lock mechanism. As a result, an overhead crane is not required and it is possible to lower the height of this tunnel compared to the H12 option.

(5) Setting up reserve areas

In the design of the repository layout, panels capable of disposing of a predetermined inventory of waste are arranged in the preferred rock areas. The latter are constrained by LDFs, which excludes faults and fractures greater than 1 km, but includes smaller features – which could impact the practicality of using particular parts of disposal tunnels/disposal holes that were initially dimensioned to the reference inventory (Section 4.5.4 (2) (iii)). Here, therefore, the required reserve disposal area to cover uncertainties in the distribution of smaller features is evaluated.

(i) Evaluation items

To define reserve requirements, the impact of smaller faults and fractures (or other highly permeable features, such as sand layers in sediments) on acceptability of waste emplacement locations has to be assessed in order to determine their impact on the panel requirement in Section 4.5.4 (2) for sufficient disposal volume. Thus, Table 4.5-21 sets the evaluation item of assuring sufficient disposal reserves.

Table 4.5-21 Reserve area evaluation items

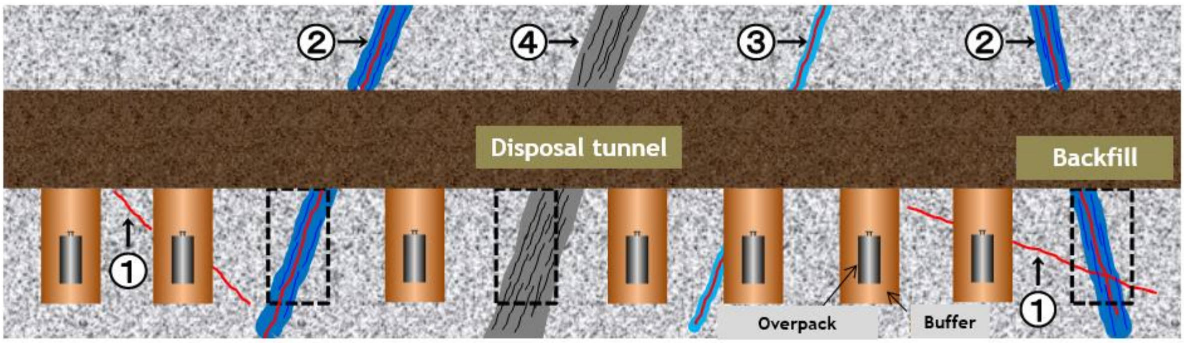
Design requirement	Detailed description of requirements for concepts assessed
Assure sufficient disposal reserves	Consider the effects of permeable features on utilisation of disposal panels to define reserve areas that will assure that the reference inventory can be disposed of

(ii) Concept of design of reserve areas

As an example, potential features that could impact the usability of disposal area within a panel for the H12V case in plutonic rock are shown in Figure 4.5-26. To define Emplacement Determining Features (EDFs), such as faults and fractures, the following characteristics impacting practicality are considered:

- If there is a large volume of water inflow, the effort required for drainage management will increase.
- When there is a locally large water inflow to disposal holes or tunnels from faults and fractures, it will be difficult to construct buffer or backfill to required quality levels.
- Local water flow can cause piping erosion of buffer/backfill with reduction of its performance.
- If mechanical strength is reduced locally, there is a risk of borehole/tunnel collapse.

Figure 4.5-27 very simplistically represents some of the issues involved.



(1) Fracture with no water inflow, (2) high permeability fault or fracture, (3) low permeability fault or fracture, (4) areas where faults and fractures decrease mechanical strength

Figure 4.5-27 Sketch of EDFs limiting disposal panel utilisation in plutonic rock (Example of H12V)

Relatively small, low permeability features (such as (1) in the figure) may not prevent waste emplacement, but raise issues requiring consideration at the time (e.g. small breakouts from the borehole wall). In the case of more permeable features, these may have sufficient groundwater inflow that emplacement is clearly precluded (e.g. (2)). Otherwise, flow may be low enough to be potentially managed by special precautions during buffer emplacement or to avoid subsequent erosion (e.g. (3)) – although such a hole might need to be abandoned if this was not practical. Similarly, larger weak zones (e.g. (4)) may also require a section of tunnel to be excluded or a hole to be abandoned. In some cases, rock improvement techniques (e.g. grouting) may reduce impacts of weak or water-bearing features, but the potential impacts on post-closure performance need to be carefully assessed in such cases. For smaller problem areas (especially the sensitive zone at the top of holes), additional stabilisation such as that shown in Figure 4.5-3 could be considered although, again, impacts on post-closure performance may need to be considered.

From such an assessment, features that are of potential concern can be assessed to determine if they are actually EDFs and would preclude quality-assured borehole drilling (e.g. low strength) or emplacement (e.g. based on water inflow rate and its impact on practicality of buffer/backfill emplacement).

For the PEM, EDFs are less restrictive and relate to practicality of disposal tunnel excavation and the emplacement of backfill (see Figure 4.4-29). For TRU waste, a number of steps involve emplacing buffer and/or backfill which would be sensitive to local water inflow, but installation of liner and grouting surrounding rock can be considered without the post-closure concerns about high pH that exist for HLW. Thus, EDFs again relate to practicality of disposal vault excavation and the emplacement of buffer/backfill.

(iii) EDF characteristics

In the study of reserve areas, EDF characteristics are set as described below.

(a) EDFs for disposal holes

For H12V, buffer and backfill emplacement are coupled in terms of assuring quality and both are very sensitive to early swelling/erosion by groundwater inflow (Section 4.4.3 (1) (i)) until final completion of the mechanical plug. Since the buffer is a key safety barrier and the extent to which its performance is expected to be degraded is proportional to the water inflow rate into the borehole, this rate is selected as the criterion for characterising LDFs. Placing the deposition hole in a more permeable zone would also imply severe problems with buffer swelling prior to backfilling in the absence of a borehole cap.

In terms of practicality, when emplacing buffer blocks it is necessary to prevent the inflow of groundwater to the disposal hole, which may require some form of in-hole water management system. Therefore, the flux of water that can be managed by such a system sets a constraint on EDFs, which is compared to a value set by the extent of possible piping erosion, with the lower of the two values used as the criterion for defining an acceptable inflow rate. Some initial assessments are made of such management techniques as described below, but further development will be needed to reduce associated uncertainties.

It is assumed that piping erosion commences after removal of the sheet used to prevent buffer wetting during emplacement, as outlined in Section 4.4.3 (1) (i), and will continue until tunnel backfilling is complete and the mechanical plug is in place (see Supporting Report 4-55). Figure 4.4-10 shows the required buffer density to meet specific design requirements. If it is assumed that piping erosion occurs only during re-saturation (see Supporting Report 4-56), Figure 4.4-10 shows that the lower limit of density would be that to meet requirement (5) (colloidal filtration) at an effective dry density of clay of $> \approx 0.8$ Mg/m^3, which would allow a total loss of 0.45 t per hole. Based on laboratory tests [119] [120], an empirical formula relates the total groundwater flow to total buffer loss, setting a flow limit of between 3.4×10^2 and 8.7×10^4 m$^{3.}$ From the maximum time delay between emplacing buffer and completion of backfilling, the minimum flow defining an EDF is 0.8 l/min, 0.8 l/min and 0.5 l/min in plutonic rocks, Neogene and Pre-Neogene sediments, respectively.

(b) EDF for disposal tunnels

For disposal tunnels, it is assumed that the impact of EDFs on their utilisation is determined mainly by water inflow impacts on excavation of the tunnel, construction of buffer (for TRU waste Grs. 1, 2 and 4H) and backfilling. In some cases, mechanical impacts could also be significant, but these are not considered at present. Figure 4.5-28 indicates issues associated with EDF specification for the example of implementing PEM DET tunnels.

Before excavating a disposal tunnel, it is assumed possible to obtain information on the risk of encountering a problematic feature by drilling a hole in advance. If a problem area is encountered, countermeasures such as grouting or modifying the excavation/support procedures can be implemented. However, in the design stage, it is not possible to estimate where in a panel such features would be found, so no quantitative assessment of the required reserve area is set at present.

When the strength of the rock is locally low, it is possible to improve the mechanical stability of the tunnel by measures such as pre-grouting, reinforcement of support systems and implementation of alternative excavation methods. However, excavation becomes difficult when water inflow at the face exceeds 300 to 500 l/min, based on past experience [121]. Therefore, to define EDF water inflow that prevents excavation, a limiting value of 300 l/min is selected.

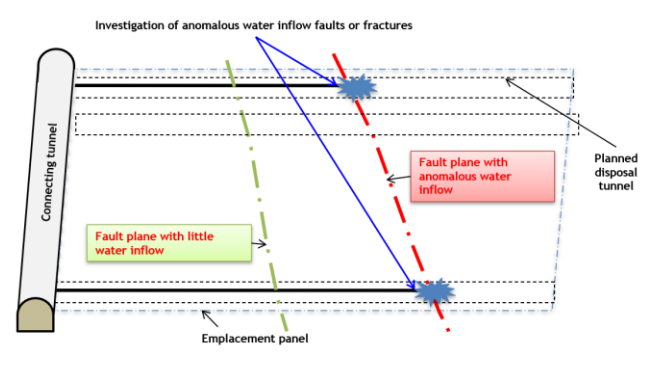
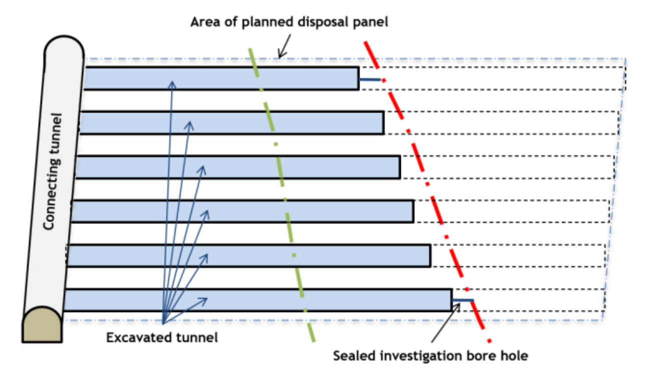
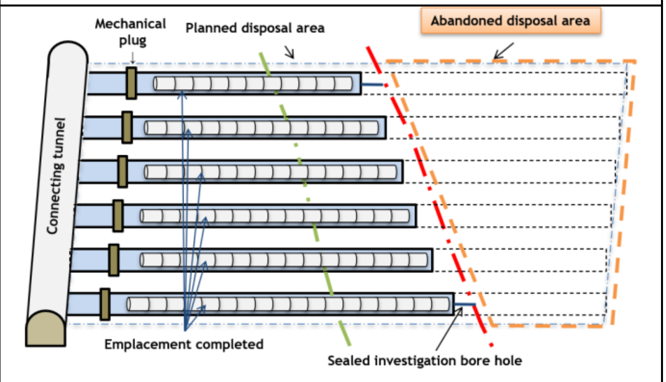
【Construction stage 1 】 Survey of emplacement panel by pre-boring from the connecting tunnel (Assumption) • Discovery of features not previously identified from characterisation work • Preliminary borehole identifies the existence of a feature with low strength and/or high water inflow	
【Construction stage 2 】 Design change based on survey results and drilling of tunnels (Assumption) • To limit the drainage volume/ensure worker safety, change the design of the panel to avoid excavation through the EDF	
【Operation stage 3】 Disposal of waste, backfilling and construction of mechanical plug at end (Assumption) • Avoid placing waste in problematic tunnel sections	

Figure 4.5-28 EDF impacts on disposal tunnels (PEM example)

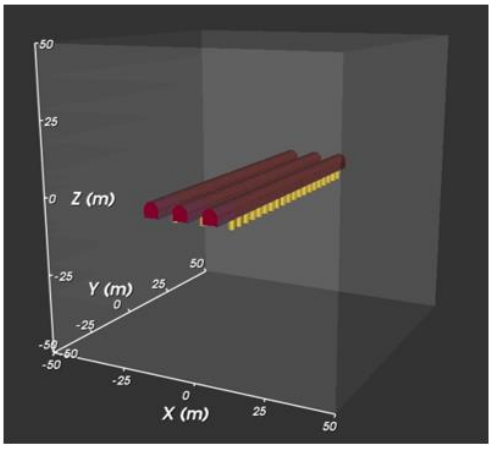
In disposal tunnels, backfilling will occur after waste emplacement. In addition, buffer will be installed in-situ for TRU waste Grs.1, 2 and 4H. Therefore, the impact of water on the construction of buffer and backfill has to be considered. For the TRU vaults, thicker lining will reduce water inflow, which can be complemented by localised grouting or drainage behind the liner [93] [122] [123]. Emplacement techniques for buffer and backfill to required quality levels will need to be developed to determine water inflow limits, hence no EDF constraint is set at present.

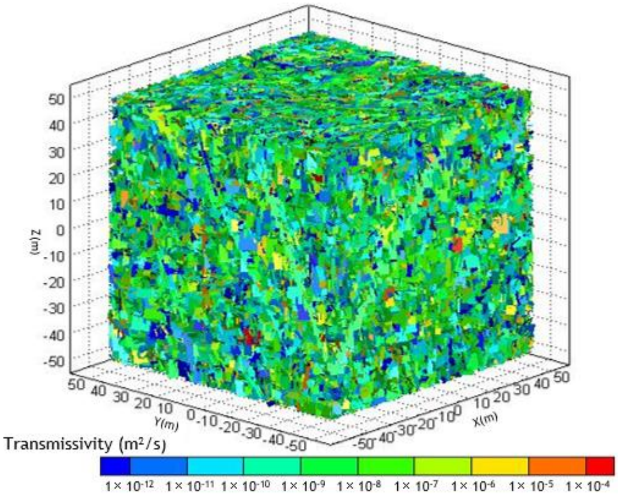
(iv) Results of reserve area assessment

(a) H12V

The definition of a relevant EDF is set by the rate of local water inflow, which can then be used to determine the unusable fraction of a disposal panel.

From Section 3.3.3 (4) (iii), stochastic three-dimensional hydrogeological models at panel scale allow inflow into disposal holes and tunnels to be determined. The hydrogeological model used represents three disposal tunnels and the surrounding rock mass, as shown in Figure 4.5-29 for the case of plutonic rocks.





(a) Model of disposal tunnels **(b) Hydrogeological DFN model**

Figure 4.5-29 3D model to evaluate disposal hole groundwater inflow (plutonic rock)

The hydrogeology is represented by a discrete fracture network (DFN) with permeability coefficients of fractures set probabilistically based on an assumed lognormal distribution (see Supporting Report 4-57 for details). To assess inherent variability, 100 realisations of the model were run. The determination of reserve areas was based on the distribution of inflow into the middle disposal tunnel.

The cumulative probability distribution of the groundwater inflow into boreholes for each of the 3 representative rocks is shown in Figure 4.5-30. It can be seen that these distributions are quite wide in the cases of plutonic rocks and Pre-Neogene sediments, but narrower for Neogene sediments, reflecting differences in the statistical distribution of fracture permeability coefficients. Assuming no countermeasures to reduce water inflow, these distributions can be compared to the EDF inflow limits set for each rock in Section 4.5.4 (5) (iii) (a) above.

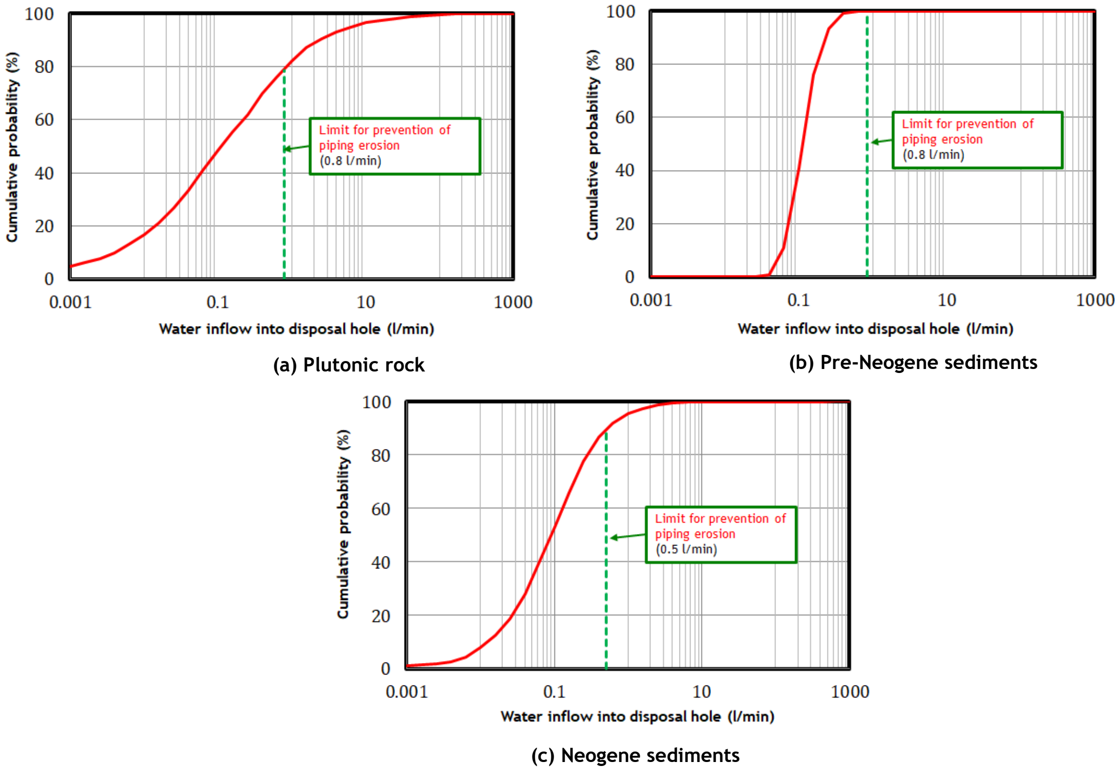


Figure 4.5-30 Cumulative probability distribution of water inflow (H12V holes)

Table 4.5-22 lists the disposal hole utilisation for each rock, ranging from 100% for Neogene sediments to 80 – 90% for the other rocks.

Table 4.5-22 Disposal hole utilisation (H12V)

Rock type	Disposal hole utilisation rate (%)
Plutonic	79
Neogene sediments	100
Pre-Neogene sediments	90

These degrees of utilisation would evidently depend on the inflow limits and other requirements considered. Further studies may be needed to assess whether current limits are appropriate. Based on these numbers, reserve areas for about ≈ 21% and ≈ 10% of the inventory are assumed to be required for plutonic and Pre-Neogene cases, respectively (for a total inventory of 40,000 HLW units, equivalent to a further 8,400 and 4,000 disposal holes, respectively). Further, as the footprint of 1 unit in plutonic rock is 44.4 m^2 (borehole pitch 4.44 m × disposal pitch 10 m) and in Pre-Neogene sediments is 71.0 m^2 (borehole pitch 4.44 m × disposal pitch 16 m), for the given hole utilisation rates these reserves are equivalent to ≈ 470,000 m^2 (plutonic rocks) and ≈ 320,000 m^2 (Pre-Neogene sediments). These reserves are incorporated into the repository layouts shown in Section 4.5.4 (6).

(b) PEM and TRU waste

For the PEM and TRU waste, fundamentally the same analysis was carried out as described for H12V above (details in Supporting Reports 4-58 and 4-59, respectively), with the model output given in terms of water inflow per metre of tunnel length. Results showed that, for

Neogene and Pre-Neogene sediments, no case exceeded the EDF cut-off value (300 l/min), set in Section 4.5.4 (5) (iii) (b) above. However, for plutonic rocks, the EDF was exceeded in 0.3% (PEM) and 0.5% (TRU waste) of the tunnel length. For such a small fraction of the tunnel, it is considered practical to apply countermeasures so that, in all cases, it can be assumed that utilisation is effectively 100%.

(v) Expansion to include reserve areas for H12V

For H12V disposal in TT panels, existing panels cannot be expanded as they are surrounded by a connecting tunnel, so a new panel is required. This could, for example, be constructed by DETs excavated off a connecting tunnel, as illustrated in Figure 4.5-31.

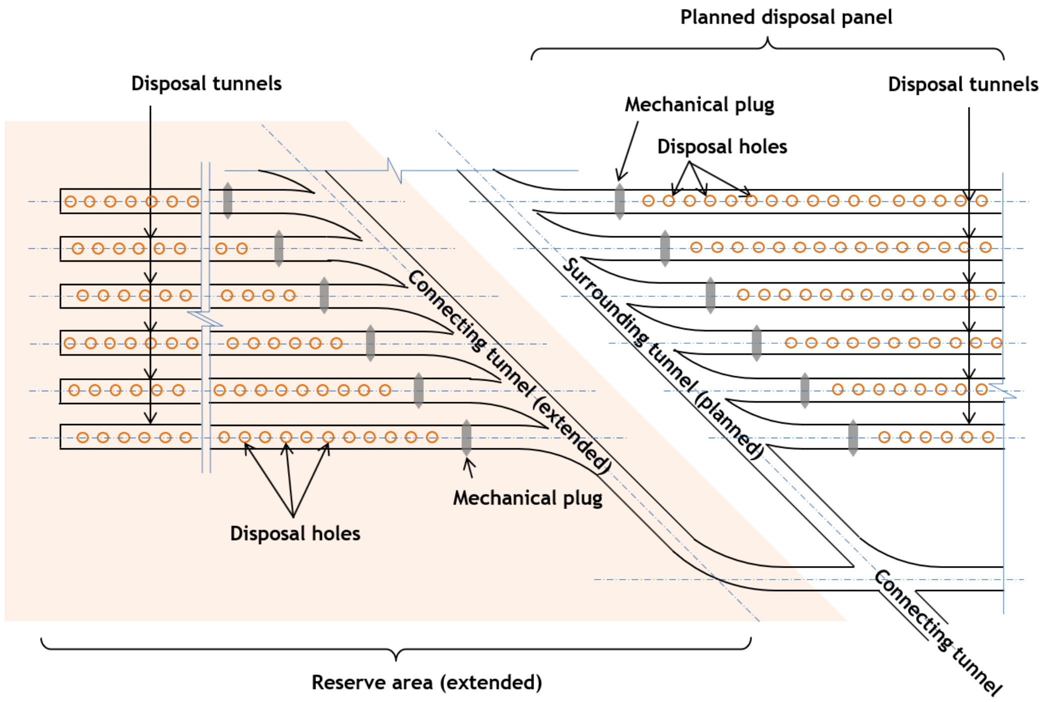


Figure 4.5-31 Expansion to include an additional panel

However, in order to use the same emplacement equipment, an appropriate junction angle between the connecting tunnel and the disposal tunnel is required.

(6) Repository Layout

The specifications of the repository layout are based on the considerations above for each rock type. In addition, requirements from Table 4.1-1 in terms of economics with respect to cost-effectiveness of construction, operation and closure are considered for different disposal concepts and disposal panel options, using the difference of the volume of excavated rock as a surrogate indicator of cost (which also correlates with environmental impact). As described in Section 4.5.1 (1), the basis for illustrating and explaining the layout of the underground facilities assumes 50 years interim storage of HLW, although the impact of emplacing waste after a storage period of 30 years is also discussed.

(i) Plutonic rocks

For co-location of HLW and TRU waste disposal, layouts of the repository for H12V and PEM variants in plutonic rocks are shown in Figure 4.5-32.

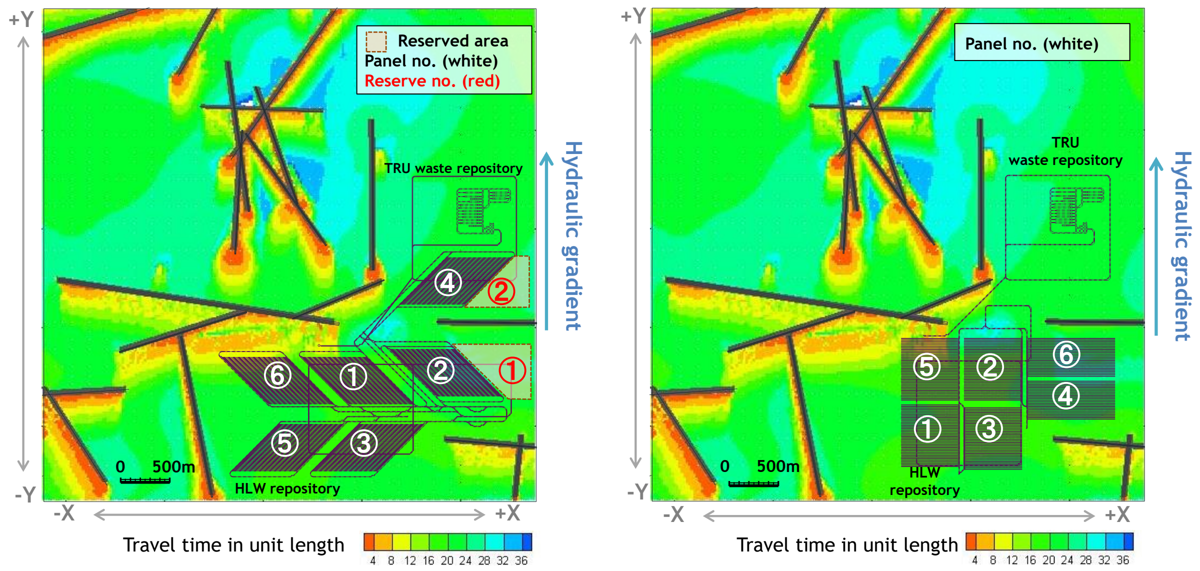


Figure 4.5-32 Layout of underground facilities (plutonic rocks, HLW interim storage 50 years)

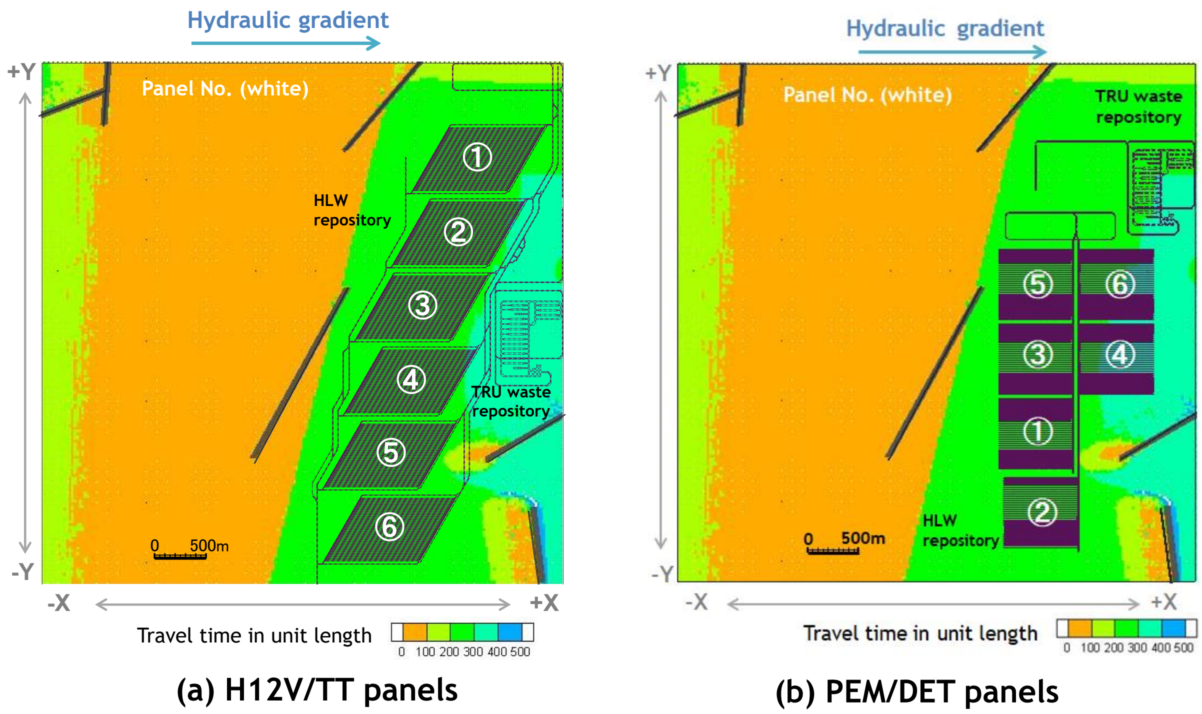
From the analysis in Section 4.5.4 (1) (ii), preferable areas in the SDM are defined (see Figure 4.5-15 (a)), in which the inventory of 40,000 waste canisters can be emplaced in 6 disposal panels as shown, together with a panel for TRU waste and required access/connecting tunnels. The panel numbers relate to the assessment of work flow, ventilation and drainage, as considered in Section 4.5.4 (4) and described in more detail in Supporting Report 4-60.

As noted in Section 4.5.1 (2), stress anisotropy is not an issue for plutonic rocks and hence panels can be laid out with disposal tunnels perpendicular to the hydraulic gradient. In addition, the TRU waste panel is located 500 m to 1,000 m downstream of the HLW. Based on the estimated disposal hole utilisation for H12V given in Table 4.5-22, the required reserve area is illustratively divided into two panels, which are placed adjacent to disposal panels 2 and 4 as shown in Figure 4.5-21 (a). In the cases of PEM and TRU waste, there is no need for a reserved area since the EDFs impacting buffer performance are so few that they could be managed by measures such as grouting. The panel numbers relate to the assessment of work flow, ventilation and drainage, as considered in Section 4.5.4 (4) and described in more detail in Supporting Report 4-60.

For the case of HLW stored for only 30 years, disposal tunnel pitch would be increased as shown in Table 4.5-7. In terms of preferred areas shown in Figure 4.5-15 (a), sufficient flexibility is available to accommodate the expanded footprint, especially if DET panels are used to make best use of better rock (details of this assessment shown in Supporting Report 4-52).

(ii) Neogene sediments

For co-location of HLW and TRU waste disposal, layouts of the repository for H12V and PEM variants in Neogene sediments are shown in Figure 4.5-33.



(a) H12V/ TT panels **(b) PEM/DET panels**

Figure 4.5-33 Layout of repository (Neogene sediments, HLW interim storage 50 years)

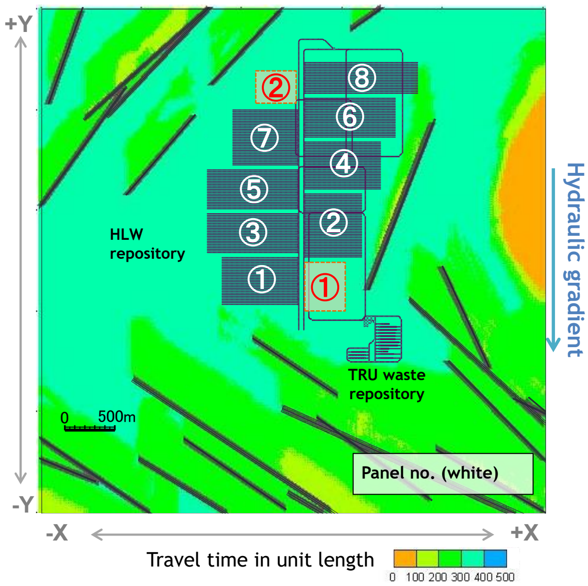
From the analysis in Section 4.5.4 (1) (ii), preferable areas in the SDM are defined (see Figure 4.5-15 (b)), in which the inventory of 40,000 waste canisters can be emplaced in 6 disposal panels as shown, together with a panel for TRU waste and required access/connecting tunnels. The panel numbers relate to the assessment of work flow, ventilation and drainage, as considered in Section 4.5.4 (4) and described in more detail in Supporting Report 4-61.

As described in Section 4.5.1 (2), disposal tunnels were arranged to maximise stability with respect to the direction of maximum principal stress (see Supporting Report 4-54). As for plutonic rocks, the TRU waste disposal panel was arranged to be downstream or out of flow towards HLW panels. As noted in Table 4.5-22, Neogene sediments do not require reserve areas.

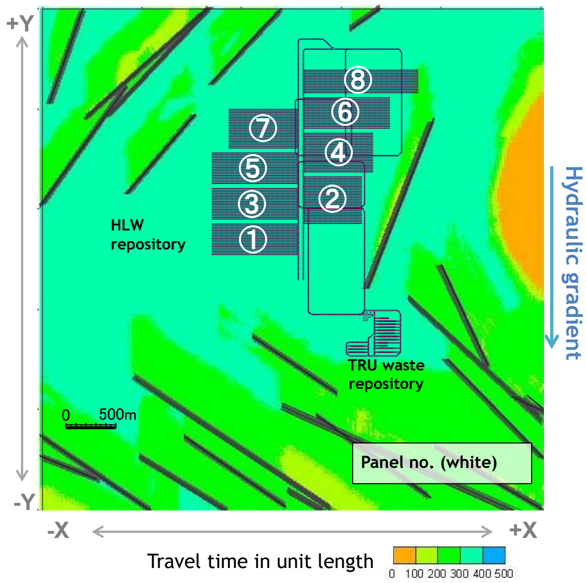
For the case of HLW stored for only 30 years, the disposal tunnel pitch would not need to be increased because of the large pitch needed to ensure mechanical stability and the lower impact of waste thermal output due to lower rock ambient temperature, as shown in Table 4.5-7.

(iii) Pre-Neogene sediments

The repository layout for Pre-Neogene sediments is shown in Figure 4.5-34. Since this rock has a folded structure and many LDFs, DET panels were considered for both H12V and PEM options in order to increase flexibility to tailor layout to preferred rock areas. In addition, since these rocks have high strength and stress anisotropy is relatively small, the disposal tunnels can be set perpendicular to the groundwater flow direction. TRU waste disposal is again downstream from the HLW panels.



(a) H12V/ DET panels



(b) PEM/DET panels

Figure 4.5-34 Layout of repository (Pre-Neogene sediments, HLW interim storage 50 years)

Based on the estimated disposal hole utilisation for H12V given in Table 4.5-22, the required reserve area is illustratively divided into two panels placed adjacent to disposal panels 1 and 2, as shown in Figure 4.5-34 (a). For the PEM and TRU cases, no reserve areas are required.

For the case of HLW stored for only 30 years, disposal tunnel pitch would be increased as shown in Table 4.5-7. In terms of preferred areas shown in Figure 4.5-15 (c), sufficient flexibility is available to accommodate the expanded footprint, especially if DET panels are used to make best use of better rock (details of this assessment are given in Supporting Report 4-52).

(iv) Comparison of excavated rock volumes and footprint

For the repository layouts described above for each rock type, the excavated rock volume was estimated from the length and cross-sectional area of all tunnels as shown in Table 4.5-23 (more details given in Supporting Report 4-62).

Comparison of H12V with the PEM clearly shows much larger excavated volumes (almost a factor of 2) for the former due to longer tunnels and the additional spoil from hole drilling. In terms of host rock, the Neogene cases tend to have significantly larger excavated rock volumes: this is due to factors such as the greater excavated volume to allow thicker tunnel support and, for H12V, the greater length of disposal tunnels due to greater pitch between disposal holes (see Section 4.5.2 (2)), despite lower volumes from access ramp and shafts due to the lesser depth of the repository. Comparing H12V for plutonic rock and Pre-Neogene sediments shows that the amount of excavated rock is greater for TT compared to DET panels.

Table 4.5-23 Excavated rock volumes for HLW disposal options

Tunnel: Length (km) Volume (x 10^4 m^3)		Panel type			DET type		
		H12V			PEM		
		Plutonic	Neogene	Pre-Neogene	Plutonic	Neogene	Pre-Neogene
Disposal Tunnel	Length	194	285	181	138	138	137
	Volume	444	613	425	258	311	255
Disposal hole	Length	166	166	166	-	-	-
	Volume	64	64	64	-	-	-
Surrounding Tunnel	Length	13	20	-	-	-	-
	Volume	33	51	-	-	-	-
Connecting Tunnel	Length	13.6	16.7	6.4	4.9	5.8	5.4
	Volume	78	123	36	28	43	31
Access ramp	Length	10.7	5.4	10.6	10.7	5.4	10.6
	Volume	61	39	60	61	40	60
Access shaft	Length	6.0	3.0	5.0	5.0	2.5	5.0
	Volume	25	13	21	21	10	21
Total	Length	403	497	370	159	152	158
	Volume	705	903	606	368	404	367

The footprint is determined for the HLW and TRU repositories as shown in Table 4.5-24. The footprint for HLW repository is in the range 3 to 12 km^2 and is largest in the case of H12V in Neogene sediments (disposal tunnel pitch is the largest of the three representative host rocks). The area for the PEM is smaller than that for H12V in the same host rock. The area for HLW repository is 11 to 28-fold that of the TRU repository.

Table 4.5-24 The footprint of the repository

Conditions			HLW			TRU waste			Area ratio
Rock type	Disposal option (HLW)	Disposal area (HLW)	Length (km)	Width (km)	Area (km^2)	Length (km)	Width (km)	Area (km^2)	HLW /TRU
Plutonic	H12V	Panel type	2.29	3.01	6.89	0.46	0.55	0.25	28
	PEM	DET type	1.52	2.17	3.30	0.46	0.55	0.25	13
Neogene sediments	H12V	Panel type	4.97	2.37	11.78	0.73	0.58	0.42	28
	PEM	DET type	3.19	1.50	4.79	0.73	0.58	0.42	11
Pre-Neogene sediments	H12V	DET type	2.88	2.09	6.02	0.46	0.55	0.25	24
	PEM	DET type	2.40	2.05	4.92	0.46	0.55	0.25	20

4.5.5 Design of underground services

The design of the underground services is, to a large extent, very likely rely on existing mining and tunnelling practice. However, some aspects and requirements will be unique to a repository and these are now assessed.

(1) Design of ventilation and cooling equipment

Ventilation and air conditioning/cooling equipment is required for both the construction and operation of the repository. For the repository layouts developed in Section 4.5.4 (6) and associated work-flows, the ventilation and cooling requirements can be specified. For HLW, construction and operation will run in parallel and independent systems are required for these two areas, with the latter established to be compatible with a radiation-controlled zone. In this section, focus is on HLW as the repository is larger and independent ventilation for radiation-controlled and non-controlled zones is required, as discussed further in Supporting Report 4-63 (which also considers TRU waste).

(i) Design requirements

The design requirements of ventilation and air conditioning equipment are outlined in Table 4.5-25. Conservatively assuming that workers are present in both construction and operational zones during normal operation, ventilation and cooling are required for general occupational safety and maintaining a suitable working environment (see Table 4.2-3).

This is broken down in order to further quantify requirements; covering maintaining oxygen concentration in working areas, dilution of combustible/hazardous gas or dust, temperature control in working areas and ventilation rate limits.

Table 4.5-25 Design requirements for ventilation and cooling equipment

Design requirements	Detailed description of requirements for concepts assessed	Specifications
Maintenance of oxygen concentration in work areas	The necessary amount of air can be supplied to maintain the oxygen concentration in the work area	Ventilation and cooling system, airlocks
Dilution of flammable gas	Required dilution of combustible gas (methane, etc.) in tunnels (depends on the geology) and safe discharge to the surface (relevant also for TRU waste)	Ventilation and cooling system, airlocks
Dilution of harmful gas and dust	Required dilution of harmful gas (e.g. gas after blasting, exhaust from machinery) and dust generated during excavation and safe discharge to the surface	Ventilation fans, airlocks, dust collectors
Maintain working area temperature	Required cooling of heat from rock and construction equipment, so that temperature and humidity of work areas are suitable	Cooling system
Tunnel air flow rate limitation	Ventilation in tunnels does not exceed the defined air flow rate standard	Ventilation fans, airlocks
Containment of RNs in case of accidents	For any accident involving leakage of RNs underground, preventing release outside the facility	Ventilation fans, airlocks, emergency ventilation equipment/control system

Relevant rules and guidelines, together with reference values for ventilation and working temperatures, are given in Table 4.5-26, noting the special case for environments where flammable gases are present. Although the Mine Safety Act is not applicable to geological disposal, the air speed limit specified therein is considered to be a reasonable design requirement.

Table 4.5-26 Regulations/guidelines for ventilation and cooling equipment

Compliance standards	Index	Reference value	Summary
Occupational Safety and Health regulations the 611 Article	Temperature	Dry bulb temperature ≤ 37 °C	Law
Ventilation technology guidelines for underground construction	Temperature	Wet bulb temperature ≤ 28 °C	Target value based on guidelines
	Air speed	0.3 m/s or more (≥ 0.5 m/s) *	
	Worker respiration rate	0.05 m^3/s/person	
Mine Safety Act enforcement regulations	Air speed	≤ 7.5 m/s	Although not covered by Mine Safety Act, set as a reference value

* When flammable gas is present

Depending on the geological environment, release of combustible gas (such as methane) during tunnel excavation may or may not be an issue. In the former case, it is necessary to take measures, such as routinely monitoring gas concentration and assuring sufficient ventilation to avoid any potential problems [124]. In addition, in such cases, it may be necessary to take additional precautions such as prohibiting the use of internal combustion engines and making electrical equipment explosion proof. Also other gases, such as Rn, could be of concern and the ventilation needs to be sufficient to keep concentration below maximum allowed levels.

In the design of ventilation equipment, the required ventilation volume [125] is calculated according to the work situation of each tunnel, with ventilation network analysis performed for routes set by consideration of the repository layout. The capacity of the required surface ventilation fans and the arrangement of baffles and regulators to adjust air flow are then set, so that the required ventilation volume can be provided where needed.

A cooling system is installed when the temperature of the work area cannot be maintained simply by air flow. As a standard for the work areas, the dry bulb temperature shall be ≤ 37 °C and the wet bulb temperature ≤ 28 °C [125]. This covers ventilation equipment design for normal conditions, but if an accident with release of radioactivity occurs, it is also necessary to assure containment within the facility. Therefore, an operational radiological safety ventilation requirement is to prevent releases of RNs (see Table 4.2-1), as described in Section 4.5.6. Section 4.5.6 also discusses ventilation needs if fire occurs, even if no radioactivity is likely to be released.

(ii) Specifications of ventilation and cooling equipment

The calculated required ventilation rates are given in Table 4.5-27 (details in Supporting Report 4-63). Of the requirements in Table 4.5-25, dilution of harmful gases and dust during construction leads to the highest ventilation rate. Because H12V requires longer tunnels and the additional drilling of boreholes, higher ventilation rates are required compared to the PEM case.

Table 4.5-27 Required ventilation for HLW options

Disposal concept	H12V			PEM		
Rock type	Plutonic	Neogene	Pre-Neogene	Plutonic	Neogene	Pre-Neogene
Panel type	TT	TT	DET	DET	DET	DET
Total required ventilation (m^3/s)	87	65	94	21	22	21

In setting the ventilation route, it is assumed that the main ventilation fans are installed at the surface on exhaust shafts (see Section 4.5.4 (4)), which drives the circulation, as is normal practice in mining [125]. Assuming manually-controlled excavation, ventilation of the rock face is particularly critical and a system based on air suction can be implemented as shown in Figure 4.5-35. Here, a booster fan is installed at the tunnel entrance and fresh air supplied to the face through a duct. An air suction duct provides an air curtain that restricts dust movement into the tunnel and allows it to be captured in a dust collector.

For the construction zone, the ventilation circuit analysis allows the main components required to be specified (wellhead fans, local fans, stoppings, etc.) as shown for the example of plutonic rocks in Tables 4.5-28 (H12V) and 4.5-29 (PEM). It should be emphasised that such rock-specific analysis is based on more detailed air flow routes than the simple conceptual representations presented in Figures 4.5-21 and 4.5-23.

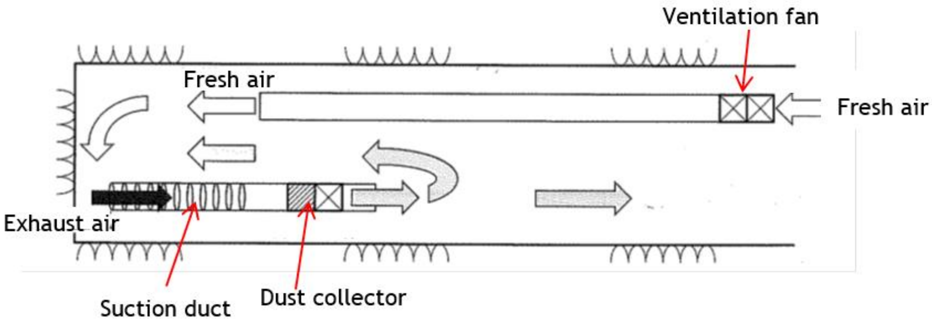


Figure 4.5-35 Ventilation during disposal tunnel excavation (air-suction option) [125]

Table 4.5-28 Ventilation equipment for construction zone (plutonic rock - H12V)

Equipment	Specification	Quantity	Summary
Wellhead fan	Rated air volume 33 m^3/s Rated total pressure 4.9 kPa	4	Exhaust for shafts 1 and 2 × 2 units on each
Booster fan	Rated air volume 17 m^3/s Rated total pressure 2.9 kPa	6	
Dust collector	Rated air volume 20 m^3/s	6	
Airlock	W (aperture) = 5 m	42	For disposal tunnels
Airlock	W = 8 m	26	For connecting tunnels
Soft ducting	φ 0.9 m	4,000 m	

Table 4.5-29 Ventilation equipment for construction zone (plutonic rock - PEM)

Equipment	Specification	Quantity	Summary
Wellhead fan	Rated air volume 33 m^3/s Rated total pressure 4.9 kPa	1	Exhaust for shaft 1 × 1 units
Booster fan	Rated air volume 17 m^3/s Rated total pressure 2.9 kPa	6	
Dust collector	Rated air volume 20 m^3/s	6	
Airlock	W = 8 m	37	For disposal tunnels
Soft ducting	φ 0.9 m	3,300 m	

To assure the required air flow (Table 4.5-27) for H12V, 4 wellhead fans with a capacity of 33 m^3/s are required whereas, for the PEM a single 33 m^3/s unit is required. Parallel excavation of 6 disposal tunnels requires this number of booster fans and dust collection units for each tunnel. The larger number of tunnels for H12V results in a complex ventilation path, requiring a larger number of air locks. In practice, the ventilation analysis also needs to consider how re-zoning after panel construction is organised, so that the reorganised flow then meets the radiation control requirements.

In terms of air-conditioning equipment, this would be installed only in locations where the wet bulb temperature exceeds the standard. For each layout, thermal analysis was carried out based on rock ambient temperatures and heat radiation from tunnel walls, excavated rock, inflowing water, machinery and the heat of hydration of concrete (details in Supporting Report 4-63).

Because of the 15 °C lower rock temperature at 500 m disposal depth, for Neogene sediments cooling equipment is not required. The repository layout for Pre-Neogene sediments required a high cooling capacity compared to plutonic rocks, due to the longer distance from the air intake shaft to the disposal tunnels. In addition, because the total length of tunnels is greater, more cooling capacity is required for H12V compared to the PEM case. In terms of the cooling method, supply of cooling water from the surface to an underground heat exchanger that cools the air is assumed, a method that is well proven in mines [126]. The actual equipment needed can be specified based on the requirements in Table 4.5-30. Note that this assessment focuses on the excavation areas and hence the impacts of heat-emitting waste is not considered.

Table 4.5-30 Cooling equipment requirements

Disposal concept	**H12V**			**PEM**		
Rock type	Plutonic	Neogene	Pre-Neogene	Plutonic	Neogene	Pre-Neogene
Panel type	TT	TT	DET	DET	DET	DET
Total cooling capacity (kW)	1,200	Not required	3,200	800	Not required	1,600

For example, for H12V in plutonic rocks, by installing 200 kW capacity cooling systems at six locations, the air temperature requirement can be satisfied. However, optimisation of cooling system locations has not yet been considered, nor any options that could utilise the waste heat.

(2) Design of drainage

Drainage requirements are assessed for the repository layouts set in Section 4.5.4 (6). It should be noted here that management of drainage water is a very sensitive (and expensive) issue in Japan. Thus, efforts to reduce water inflow to the extent possible are justified (an additional benefit being that the environmental impact is also reduced).

(i) Design requirements

The design requirements for drainage are given in Table 4.5-31, which focuses on operational safety related to maintaining a safe working environment (see Table 4.2-3).

Table 4.5-31 Drainage design requirements

Design requirements	Detailed description of requirement for concepts assessed	Specifications
Assuring drainage capacity	All water inflowing underground can be safely drained and pumped to the surface for disposal	Drainage capacity

In order to ensure sufficient drainage capacity, the water inflow into specific layouts has to be calculated.

(ii) Required drainage capacity

Required drainage (and the location of pumps and pipes) is defined for the layouts established in Section 4.5.4 (6) (details are given in Supporting Report 4-64). In order to estimate the volume of water inflow, the method used accounts for both the EDZ depth and any grout improvement (grouting to reduce water inflow) associated with excavation of tunnels [127]. An appropriate cement-based grout is assumed, with a composition that will not risk perturbation of EBS performance [128] [129]. For illustrative purposes, total inflows are estimated for different layouts based on pressure heads experienced and discharge reduction due to grouting, for an arbitrarily assumed grout depth of 3 m. Calculated groundwater discharge rates are given in Table 4.5-32, but these would clearly need to be re-assessed for site-specific layouts and implementation plans.

Table 4.5-32 Calculated groundwater discharge (grout depth 3 m)

Rock type	HLW (m^3/min)		TRU waste (m^3/min)
	H12V	PEM	Vault
Plutonic	17.3	10.4	4.6
Neogene	4.6	1.4	1.2
Pre-Neogene	3.2	3.0	2.3

For HLW, in all rocks, discharge is less for the PEM case compared to H12V because of the shorter total tunnel length (see Table 4.5-23 for tunnel lengths). In addition, for both HLW options and TRU waste, plutonic rocks give higher discharges than the other rocks because of a higher average hydraulic conductivity.

In order to determine the capacity of drainage infrastructure (drainage pipe diameter, number of pumps and required power), an allowance for variations of inflow volume (assumed to be a factor of three) is used to derive the specifications shown in Table 4.5-33.

Table 4.5-33 Drainage facilities capacity (for grout width 3 m)

Rock	Emplacement method	Design basis drainage (m³/min)	Head (m)	Drain pipe inner diameter		Number of pumps	Required power (kW)
				Nominal diameter	(mm)		
HLW repository (3 drainage shafts)							
Plutonic	H12V	51.9	1,000	350A	318	6	20,100
	PEM	31.2	1,000	250A	237	6	12,180
Neogene	H12V	13.8	500	250A	249	3	2,700
	PEM	4.2	500	150A	151	3	810
Pre-Neogene	H12V	9.6	1,000	200A	191	3	3,780
	PEM	9.0	1,000	200A	191	3	3,450
TRU waste repository (1 drainage shaft)							
Plutonic	-	13.8	1,000	300A	284	2	5,380
Neogene	-	3.6	500	250A	249	1	680
Pre-Neogene	-	6.9	1,000	300A	284	1	2,630

It was assumed that pumping from the bottom of the drainage shaft to the surface utilises a super high lift, large capacity pump. The material of the drainage pipe is carbon steel (JIS G 3454), which has a working pressure of about 10 MPa (equivalent to a head of 1,000 m).

4.5.6 Safety measures during construction and operation

The design of the underground services presented in Section 4.5.5 is based on normal operational conditions. Normal conditions include inherent variability (e.g. of water inflow as considered above), but not accidents or equipment malfunctions. This is a requirement for nuclear facilities, which has been extended to repositories. Also abnormal conditions are considered in the design and currently include:

- Drops during transportation and emplacement of waste.
- Fires and explosions: caused by ignition of equipment used in underground facilities, accumulation of flammable gas, etc.
- External power loss: failure of services due to loss of electricity supply from external power sources.
- Other equipment failure: damage to equipment or loss of services due to malfunction, incorrect operation by workers, etc.

The need to physically separate underground construction from operation is considered in the layout of disposal panels and connecting tunnels, to separate radioactive areas from non-radioactive, but the current assessment focuses on issues during operation, with no assessment of potential impacts from construction activities. Furthermore, the current assessment looks at incidents individually (without considering common mode failure). Such coupling will be considered in the future. Issues not directly considered in this Section include:

- Direct radiation exposure to the public from the repository, due to effectively complete shielding by the overburden.
- Direct worker radiation exposure from transport and emplacement of the waste, as these actions are assumed to be under remote control and zoning will prevent workers approaching the waste, even in abnormal conditions (except for special cases during recovery work).
- Movement of active faults that cause direct disruption underground, as the presence of these will be excluded by the site selection process (see Sections 3.2.2 (1) (i) (c), 3.2.2 (2) (i) (c) and 3.2.2 (3) (i) (c)).
- Seismic impacts on tunnels: these are provisionally designed to withstand expected events, but more detailed assessment is only reasonable in the future for specific site conditions.
- External surface perturbations, such as tsunami, floods, typhoons, tornadoes, etc., would not directly affect the repository, but could be associated with risks such as inundation or loss of surface services. Again, these are sensible to assess only after the environment of specific sites is defined.
- Issues associated with illegal intrusion into waste management facilities, which will be excluded by the design of surface facilities.
- Relevant infrastructure related to abnormal event management (e.g. monitoring, radiation dose measurement, communications, etc.), which are also presently assumed to be located at the surface.
- Prevention of abnormal incidents involving radiation risks, which is covered in Chapter 5.

The identification and description of the abnormal states assessed are presented in more detail in Supporting Report 4-65.

For the case of HLW, as mentioned in 4.2.4 (1) (i), all handling underground involves waste within a massive overpack, possibly complemented by transport shielding or a surrounding PEM. The assessment thus needs to consider if, for any of the abnormal conditions listed above, the key safety function of containment during operation could be lost and RNs released. Release of RNs requires both that the overpack is severely damaged and also damage to the stainless steel fabrication canister, so that the glass matrix is exposed and could release contaminants in a form transportable by air or water.

In the case of TRU waste, RNs may also be released if the waste package, container and waste matrix are damaged. The situation here is more complex, as packages (especially waste package A) are less protective than the HLW overpack. Gr.3 is potentially flammable and TRU waste matrices may be less robust than HLW glass. TRU waste will thus be a priority for further studies of perturbation scenarios.

The stepwise implementation of safety measures to prevent abnormalities developing or propagating into accidents is outlined in Figure 4.2-7, emphasising the concept of defence in depth. Nevertheless, despite multiple safety measures to prevent serious damage to waste packages, additional precautions are introduced to reduce the probability and consequences of any scenario leading to possible RN releases from the repository.

(1) Package drops

In the repository, the main risk of a drop for H12V is currently considered to be associated with the process of lifting the overpack:

- At the bottom of the access ramp, overpack transfer from the transport vehicle to the emplacement device using an overhead crane (see Section 4.5.4 (4) (iii)).
- Within disposal tunnels, lowering overpacks into disposal pits by the emplacement machine (see Section 4.4.3 (1) (i)).

Possible initiating events for overpack drops and countermeasures against them are summarised in Table 4.5-34.

Table 4.5-34 Safety measures against HLW overpack drops

Possible abnormal condition	Probability reduction measures	Consequence reduction measures
Breaking of the lifting wire	Regular inspection and maintenance of equipment Double lifting wire	Handling height limitation
Lifting with incomplete grip	Regular inspection and maintenance of equipment Interlock that does not allow lift unless it is secure	Handling height limitation
Accidental release during lift	Regular inspection and maintenance of equipment Interlock that does not release grip unless package is completely lowered	Handling height limitation

Drops could involve failure of a lifting wire, lifting without a fixed grip and accidental release – the probabilities of which can be reduced by regular inspection and maintenance, together with more robust designs including double wires and grip interlocks. In all cases, consequences can be reduced by fixing a handling height limit, which is physically impossible to exceed. For the PEM, there are no significant lifts involved - even when raised by the emplacement machine, the clearance is small and, even in the event of a drop, the risk of damage to the overpack is negligible due to protection by the PEM handling shell and contained buffer.

TRU waste package B is emplaced in the disposal vault by an overhead crane gripping a twist-lock mechanism (see Section 4.4.2 (2) (ii) (b) and Supporting Report 4-21). This lifts waste packages from the transport vehicle, moves them within the vault and lowers them into position on a waste stack (see Section 4.4.3 (2)). Fundamentally, issues associated with drops are the same as in Table 4.5-34. For TRU waste package A, lifting and emplacement is by forklift truck, so an interlock mechanism that does not allow lifting of the waste package if fork insertion is incomplete is necessary. Despite these safety measures, the evaluation of waste drops is covered in Section 5.4.2 (1).

(2) Fire

Fires require combustible materials, an ignition source and oxygen: eliminating any one of these will usually prevent the occurrence of fires. An exception involves materials that could self-ignite, with TRU Gr.3 representing the only relevant case – which will be examined further in the future.

Although the HLW overpack is clearly non-combustible, there is a possibility of other combustible substances being present in the HLW repository:

- Access ramp; fuel and wheels of the road transport vehicle (see Figure 4.5-36).
- Bottom ramp; lubricant for overhead crane used for overpack transfer from ramp transporter to emplacement machine (H12V only).
- The fuel and wheels of the H12V emplacement machine.

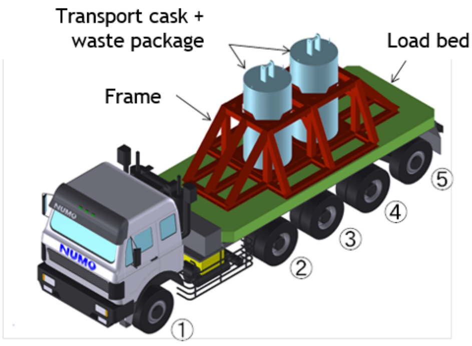
Based on past underground fires [130], it is considered to be effectively impossible to exclude ignition sources completely, especially for transport vehicles. For the maintenance of the working environment (Section 4.5.5 (1)) ventilation will ensure the presence of sufficient oxygen. Possible initiating events for fires and countermeasures against them are summarised for HLW in Table 4.5-35.

Table 4.5-35 Safety measures against fires (HLW)

Possible abnormal condition	Probability reduction measures	Consequence reduction measures
Fire in equipment handling waste	• Limitation of ignition sources • Maintenance of vehicles and devices that could serve as ignition sources • Limited use of combustible material • Use of non-flammable and flame-retardant materials	• Use of non-flammable and flame-retardant materials • Thermal anomaly detection monitors, fire alarm equipment • Fire supressing equipment (automatic to the extent possible) and fire-fighting actions

Measures to prevent the occurrence of fires in underground facilities include limiting ignition sources and combustible materials to the extent possible, together with regular maintenance of vehicles and equipment that may be sources of ignition or fuel. When a fire (or precursor such as heat or smoke) occurs, rapid fire detection and response (automatic fire extinguishing equipment or active fire-fighting) are important to minimise impacts and prevent the spread of fire. The widespread use of non-combustible and flame-retardant materials is also considered to be effective in preventing the spread of fire. Ventilation control measures could also be effective and will be examined further in the future.

In terms of the assumed equipment in the operational part of the repository, the greatest fire risk is the road transporter for H12V overpacks, PEMs and TRU waste packages (illustrated in Figure 4.5-36, along with a breakdown of the flammable components present). The spread of fire to bituminised waste (Gr.3) must be prevented, but there is qualitatively no difference in the handling compared with other wastes.



Combustibles	Quantity	Calorific value (MJ)
Engine oil	75 l	2,933
Diesel fuel	200 l	7,540
Gear oil	93 l	3,636
battery	122 kg	2,684
Tyres (front)	147 kg	1,810
Tyres (rear)	1,029 kg	12,669

Figure 4.5-36 Heat generated from a transfer vehicle fire

This vehicle has a longer travel time than the H12V emplacement machine and requires fuel for descent and return to the surface, so would have a larger tank than the H12V emplacement machine. Other sources of combustible material, such as lubricating oil for overhead cranes, are estimated to be minor by comparison, so the assessment of fire countermeasures focus on transport vehicles in the access tunnel (see Supporting Report 4-66), as captured in Table 4.5-36.

Table 4.5-36 Safety measures against transport vehicle fires

Possible abnormal condition	Probability reduction measures	Consequence reduction measures
Ignition of tyres (e.g. due to abnormal heating caused by brake failure)	• Inspection and maintenance of transport vehicle • Abnormal heat detection device for wheels	• Protection provided by truck bed, steel frame and transport shielding • Abnormal heating detection device for vehicles, on-board fire extinguishing equipment • Tunnel fire detection and extinguishing equipment
Ignition of light oil leaking due to failure of transport vehicle or collision	• Inspection and maintenance of transport vehicle • Interlocks and protection devices to prevent runaway accidents or minimise their consequences	• As above

As noted in Table 4.5-36, credible fires could start in the tyres (e.g. as a result of brake over-heating) or ignition of spilt fuel (e.g. as a result of a collision). Apart from reducing risks of both by rigorous inspection and maintenance of the transport vehicle, a countermeasure for the former could involve installing a detector for abnormal heating of the wheels and for the latter, could involve interlocks and protection (e.g. runaway capture zones) to reduce the risk and consequence of collisions (see further subsection below on equipment failure). Fires on ramps can be particularly problematic due to chimney effects, so ventilation controls (e.g. automatic fire doors) will also be considered in the future. Future work will also consider alternative means of transport to that of ramps.

Basically, the same transport vehicle is assumed for H12V overpacks, PEMs and TRU waste packages, with only the specifications of the transport unit being different. For all 3 types of load, a preliminary assessment of simple fire and collision scenarios are considered in Section 5.4.2 (2).

(3) Explosions

For the operational areas of the repository, explosions can result from the accumulation of combustible gas, arising from the rock, waste or repository equipment/materials, in the presence of oxygen and a source of ignition. A representative initiating event for explosions and countermeasures against it are summarised in Table 4.5-37.

Table 4.5-37 Safety measures against explosions

Possible abnormal condition	Probability reduction measures	Consequence reduction measures
Rise in flammable gas concentration in a tunnel	• Installation of flammable gas detection and alarm system at key points • Dilution of flammable gas below explosion point by ventilation • Checks and maintenance of ventilation equipment and gas monitors • Excluding potential ignition sources to the extent possible	• Blast doors • Ventilation controls • Power cut-outs

As noted in Table 4.5-25, tunnel ventilation is specifically designed to keep problematic gases well below their explosion point. In addition, equipment and working procedures will be designed to eliminate ignition sources to the extent possible. The above measures, combined with special protective equipment if needed (e.g. catalytic converters), should reduce explosion risks to a negligible level. In any case, gas detection and alarm devices will be installed in tunnels and response plans will be developed for scenarios in which this may be a problem.

It should be noted that, in this report, the SDMs from Chapter 3 do not assume presence of methane or other flammable gas. However, in some locations, Japanese Neogene sediments contain significant quantities of methane. When investigating sites, starting from the LS, the presence of combustible gases must be considered.

(4) Loss of external power

If all external power to the repository site is lost, it is assumed that this will impact many different processes and services. Existing nuclear facilities reduce this risk by having several independent power supply lines and, even in the event that all fail, backup power generators on site that will provide sufficient power to run important services for an extended period of time. In the worst case of total site blackout where both external and local power is lost, batteries would allow key, safety-critical services to run long enough to bring the site to safe shutdown conditions.

In terms of assessing impacts on underground facilities, the focus is on loss of power from the surface. Again, as for nuclear facilities, at least 2 independent power supply routes would be planned, but it is possible that power could be lost due to either surface blackout or a perturbation that disrupts all power supply routes (e.g. a major earthquake). It is notable that the impacts of these cases would be somewhat different (e.g. if surface power still available, exhaust fans at the top of shafts would still drive ventilation) but, for present assessment, the focus is on the former case. Table 4.5-38 thus focuses on impacts of the loss of external power supply to underground facilities and associated countermeasures to reduce probability and consequences of these, without considering the initiating event causing this loss. More comprehensive assessment of power loss scenarios will be carried out for specific sites/disposal concepts in order to develop countermeasures. Nevertheless, in general, the probability of loss of such supply is reduced by increasing the number of independent power sources/supply routes.

Table 4.5-38 Safety measures against impacts of loss of external power supply

Possible resulting abnormal condition	Probability reduction measures	Consequence reduction measures
Drop while handling waste	• Multiple independent power sources and distribution lines • Mechanical gripping device (no power required to maintain grip) • Fail-safe lifting cable brakes in event of power loss	• Backup power to allow lowering to safe position • Handling height restriction
Flooding of facilities following loss of drainage	• Multiple independent power sources and distribution lines	• Backup power for underground pumps • Layout of drainage/capacity of sumps • Failsafe closure of bulkhead doors
Accumulation of flammable gas due to loss of ventilation	• Multiple independent power sources and distribution lines • Catalytic convertors	• Backup power for underground ventilation control • Failsafe closure of bulkhead doors
Loss of fire detection and extinguishing equipment	• Multiple independent power sources and distribution lines	• Backup power for key safety-critical components • Failsafe closure of bulkhead doors
Loss of control system	• Multiple independent power sources and distribution lines	• Backup power for key safety-critical components

The possible abnormal conditions during the process for lifting and moving overpacks/PEMs/waste packages are outlined in Section 4.5.6 (1). For the specific case of loss of power, it is important to include mechanical interlocks/brakes that fail-safe in the event that power is lost.

Ventilation requirements are outlined in Section 4.5.5 (1). In the case of loss of power, workers would be immediately evacuated and, even if ventilation was lost, would be able to escape to surface or to a suitable-equipped safe refuge. If ventilation was lost, as considered in Section 4.5.6 (3), the main concern would thus be accumulation of combustible gas leading to a fire or an explosion. To prevent this abnormal state from occurring, catalytic convertors could be installed, while impacts can be reduced by backup power for key ventilation controls (e.g. booster fans) to facilitate the action of the convertors and failsafe bulkhead doors to reduce consequences of an explosion.

Section 4.5.5 (2) outlines the drainage system concept which, in the event of failure, could lead to flooding of at least some part of the repository. Although this may not lead to a radiological risk, flooding may damage underground infrastructure and recovery may be costly and hazardous. To prevent flooding, backup power for pumps and a drainage layout with large sumps that provide time for power recovery will be implemented. General layout, potentially combined with the option of bulkhead doors that failsafe closed, could reduce risks to more sensitive areas by diverting water to empty tunnels/vaults.

Section 4.5.6 (2) overviews fire protection measures, which can be assured, even in the event of loss of external power, by backup power to safety-critical components. Again, the option of bulkhead doors that failsafe closed could be considered to both protect sensitive areas and smother fires in areas where no workers are present.

Because of the multiple impacts of power loss, central control plays a key role in incident management – assuring safety of all workers and bringing the site to a safe shutdown. It is thus important to identify and provide assured power to all safety-critical components of this system.

(5) Equipment failure

Many of the abnormal states considered above can be traced back to perturbations (impacts, fires, floods, etc.) caused by equipment failure or malfunction due to operator error. There are cases, however, when complex abnormal states can develop which contain several of these perturbations as a result of a type of common-mode failure. When such scenarios are identified, special efforts must be made to provide defence in depth in terms of the initiating event, reducing probability of occurrence to the extent possible and providing countermeasures to reduce consequences if it does occur (as explicitly required by nuclear regulations). This is illustrated for the case of loss of control of the waste transport vehicle in the access ramp, as a high-speed collision could result in a physical impact on the waste package, a fire, damage to the tunnel liner, loss of a ventilation inlet – all causing further possible perturbations.

If a failure occurs in the braking system of the transfer vehicle while descending the access slope shaft, a runaway could occur with speed continuously building up leading to an eventual collision. Safety measures to prevent this or reduce consequences are shown in Table 4.5-39.

Table 4.5-39 Safety measures against runaway of the waste package transporter

Possible resulting abnormal condition	Probability reduction measures	Consequence reduction measures
Transport vehicle runaway due to malfunction or operator error	• Regular maintenance of transport vehicles • Independent failsafe speed restriction mechanisms	• Speed restriction by horizontal ramp sections • Capture by runaway escape or arrestor sections • Robust waste packaging

In order to prevent the occurrence of the abnormal state, regular maintenance of the transport vehicle is complemented by provision of one or more independent, failsafe breaking or speed-limiting mechanisms. In the event that the vehicle cannot be stopped by on-board equipment, maximum speed can be limited by including horizontal ramp sections and it can be captured in runaway escape or arrestor sections. Even though the probability of such a runaway resulting in a collision with the tunnel wall may be very low, the consequences are evaluated further in Section 5.4.2 (5).

(6) Mitigation measures for radiological impact

Sections 4.5.6 (1) to (5) above have considered a range of abnormal conditions and measures that can reduce their likelihood of occurrence and their consequences, aiming to ensure that the fundamental safety function of containment of radioactivity by the robust waste package is not lost. However, as highlighted in the US WIPP radioactivity leakage case [130], failures in QA of waste conditioning and packaging can give rise to unanticipated, abnormal conditions leading to loss of containment. Although no particular scenario causing this is identified for the NUMO case, radiation monitors will be located in all sensitive areas and, in the event of detection of an anomaly, emergency drainage capture/ventilation through

HEPA filters would be initiated in order to capture as much radioactive material as possible and confine contamination to the site, thus preventing any significant release from the repository.

(7) Worker safety

For workers involved in construction and operation in underground facilities, safety measures in the event of fires, flooding, rock falls, rock bursts, etc. are described.

In terms of fire protection measures, limiting use of combustible material and presence of ignition sources, together with fire detection and extinguishing equipment, are the same as listed in Table 4.5-34. However, when using explosives for excavation, absolute exclusion cannot be applied and conventional mine safety measures are implemented to reduce associated hazards. In addition to these measures, in order to ensure the safety of the workers, it is planned to make fire-fighting activities remote-handled, to the extent possible. All personnel not involved in firefighting operations require evacuation from underground facilities; as noted in Section 4.5.4 (4) this is allowed for by independent evacuation routes through connecting tunnels to access ramps/shafts with multiple emergency shelters in case these cannot be used. In addition, considering that the construction and operation underground are carried out in parallel, zoning will strictly separate these activities and, for the case of fire, airlocks, fire doors will prevent both spread of fire and smoke penetration between these zones.

The hydrostatic pressure at repository depth, as noted in Section 4.3, is 5 MPa or more. Such high groundwater pressure presents a flooding risk, which is countered by measures such as proactive grouting, rapid liner installation and assuring sufficient margins in the drainage system (see Section 4.5.5 (2) (ii)) based on the current state-of-the-art in civil engineering technology for tunnel construction.

Because the lithostatic pressure is also high deep underground, there are risks of face collapse and rock bursts during excavation. For both these cases, risks can be reduced by appropriate design of tunnel layout and excavation technology/support structures based on information on the geological environment obtained during site survey and construction, with characterisation drilling ahead of face excavation and appropriate rock stabilisation measures applied as needed.

Since the time from the start of construction to the completion of closure extends for over 50 years, deterioration and potential failure of tunnel support materials and infrastructure equipment installed underground has to be assumed. To reduce risks, regular inspections, maintenance, and replacement/upgrading of equipment will be considered. Furthermore, it is considered cost-effective to reduce risks by setting up backups for essential services such as power supply, drainage and ventilation – assuring that, at the very least, requirements for safe worker evacuation can be assured even for a worst-case scenario.

It is recognised that, in addition to the physical safety measures mentioned above, administrative and organisational factors also play a role in assuring worker safety. This includes implementation of a safety culture throughout NUMO and all support contractors and specific actions such as formal risk management of all activities, education and training of all relevant staff, implementing resilient communication systems to manage responses to perturbations and assuring that all experience with anomalies is captured and analysed to feed back to improvement of countermeasures and hence prevent recurrence.

4.5.7 Engineering technology for construction, operation and closure of underground facilities

In this section, the state of development of engineering technology for construction, operation and closure of underground facilities is summarised. A particular focus is quality-assured construction of the EBS, as outlined in Section 4.4.3.

(1) Construction of underground facilities

With regard to the excavation of the tunnels shown in Section 4.5.2, a construction method with a well-established track record of safe implementation for relevant civil engineering work in similar geological environments will be selected. For all the tunnels, shafts and ramps, the NATM can be selected as a standard method of excavation based on wide experience in Japan. This method uses steel supports, shotcrete and rock bolts in combination to maximise the support capacity, is excellent in dealing with changes in rock quality, and is economical. In addition, for the case of H12V, disposal holes are drilled following the completion of the overlying disposal tunnel. To date, demonstration tests have been conducted using large-diameter and full-section drilling machines developed specifically for this purpose [131] [132]. From these results, although drilling of such disposal hole can be implemented with existing technology, it is considered important to improve drilling efficiency in the future. Details of these drilling techniques are given in Supporting Report 4-67.

During actual construction, it may be difficult to excavate deep tunnels under certain conditions, such as encountering a large fault or structural discontinuity, where the rock strength is low and/or water inflow is large. For this reason, with URL projects, the applicability of relevant grouting methods before and after tunnel excavation has been demonstrated [122] [123]. However, while underground engineering can handle most situations, encountering conditions where no clear engineering fix is at hand might result in considerable delay in the excavation activities. Further studies of such problem areas from an engineering perspective will provide guidance to site characterisation, with the aim of allowing layouts to be planned that avoid these to the extent possible.

(2) Backfilling of disposal tunnels and installation of plugs

Backfilling of disposal tunnels has to be assured to meet required specifications (see Section 4.5.3 (1)), which would require confirmation methodology. From domestic and foreign experience to date, various methods utilising pre-compacted blocks, in-situ compaction, spraying, pellet infilling and fluidised emplacement are potentially applicable. The actual backfilling method and implementation (either manual or remote handled) will be selected in consideration of the characteristics of each disposal tunnel and construction efficiency for specified geological environments.

Additionally, for H12V, a massive bentonite block, with the same specifications as buffer material, is emplaced using remote handled equipment in the upper part of disposal hole after installing the EBS. As no borehole cap is currently considered, backfilling the overlying tunnel must be carried out as quickly as possible thereafter to avoid loss of quality due to swelling or piping erosion.

TRU vault backfilling could be manual, due to radiation shielding of the already emplaced EBS materials, so in-situ compaction with superior construction efficiency and effectiveness for backfilling to relevant standards is assumed (although remote operation may be considered in the future to reduce worker risks). In addition, for areas with tight spatial restrictions, this can be combined with spraying methods, which have been seen to be practical in full-scale demonstration tests in underground cavities [85].

For the PEM, the gap between the PEM and the disposal tunnel is assumed to be backfilled by automated (possibly tele-operated) methods (pellet infill or spraying [13], [133]) due to the practical challenges resulting from the confined spaces between both the PEM and the rock wall, as well as radiation protection considerations (assuring doses are as low as reasonably achievable - ALARA).

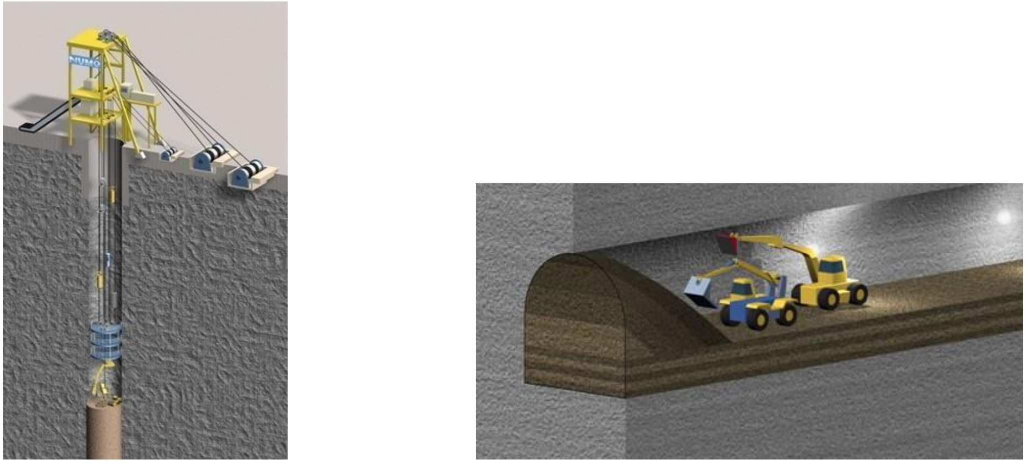
At the end of the disposal tunnel, a mechanical plug made of reinforced concrete is assumed to be installed in order to prevent the expansion of the backfilling material into the unfilled space and resultant loss of quality (Figure 4.5-12). In order to construct the plug, it is necessary to carry out tunnel support removal, excavation of the plug widening section (notch), rebar and formwork assembly and then concrete emplacement [134]. The concrete plug construction technology is based on experience found in the national oil and gas storage knowledge base [135]. At present, full scale demonstration tests of plugs based on various design concepts are ongoing to assess engineering practicality in underground research facilities in Japan and abroad [136] [137] [138] [139]. Nevertheless, it is clearly undesirable to carry out all such work after waste emplacement (especially for H12V as this requires tunnel sealing as quickly as possible) and hence a concept needs to be developed in which as much as possible of the structure is produced during the initial panel excavation.

(3) Repository closure

As described in Section 4.5.3, closure of the repository is intended to isolate the repository from the surface, sealing all access (shafts, ramps) together with connecting tunnels and other tunnels used for construction and operation of the repository. All exploration boreholes are also sealed and hydraulic plugs emplaced as required. After backfilling, to prevent human intrusion, high strength concrete plugs are emplaced at key surface access points (see Figure 4.5-10 (b)).

From the viewpoint of construction efficiency, the in-situ compaction method is effective for backfilling of connecting and access tunnels. In the case of horizontal tunnels and ramps, backfill material is poured onto the lower half of the tunnel and compacted to a predetermined density with a roller compactor (such as a vibrating roller), with the upper half poured to form a slope which is compacted to a pre-determined density by a compaction vibrator [140] (see Figure 4.5-37 b). For shafts, it is easy to backfill while sequentially compacting (See Figure 4.5-37 a).

For the construction of hydraulic plugs, stacking pre-compacted bentonite blocks and filling interface gaps with blown bentonite pellets is effective and has been confirmed by full-scale in-situ testing [104], but other options may be more practical. Since the installation of a notch in the rock (to cut the EDZ) is a new excavation, it is necessary to select a construction method that does not form a further damaged area outside the notch (for example, combining line drilling and rock-splitting methods [134]).



(a) Access shaft (b) Tunnels and ramps

Figure 4.5-37 Illustration of backfilling work

Boreholes from the surface are potential short circuits between the repository and the surface if there is a significant upwards hydraulic gradient (e.g. artesian conditions), but must be backfilled and sealed in any case due to regulatory requirements. Based on previous empirical tests, backfilling with compacted bentonite in low permeability rock sections may be effective, although such clay may be eroded in permeable fracture zones, in which case, concrete plugs may be more suitable [101] [141] [142]. Alternative methods demonstrated at depths of several hundred metres or more involve bentonite emplacement within a perforated copper pipe or as a cylindrical block which is pressed out of a container at depth, in both cases sealing the hole as the bentonite swells following groundwater uptake [101] [142]. However, there is no standard methodology and the applicability of such methods will be confirmed by borehole tests. Finally, while borehole sealing requirements would be site specific, overseas experience suggests (i.e. SKB TR-12-08) that using even relatively high permeability backfill (e.g. sand or rock spoil) for the purpose of borehole backfilling could be sufficient.

4.6 Design of surface facilities

The surface facilities receive and handle the waste transported from interim stores and support the work of construction, operation and closing of the repository (see Figure 4.2-5). The functions of these facilities are diverse and they should be laid out appropriately based on the characteristics of the site topography. It is necessary to construct many of the surface facilities prior to construction underground and these will eventually be removed during closure of the repository [2]. Surface facilities for both HLW and TRU waste were briefly described in Section 4.2.3 (4). In this report, the focus is on facilities for receiving, inspection, and encapsulating/packaging HLW and TRU waste, for which radiation protection is an issue. Other facilities that do not handle radioactive waste are similar to conventional industrial or commercial buildings and will be considered only later in the site selection process.

4.6.1 Assuring safety in the design of surface facilities

Prior to the design of waste acceptance/inspection/packaging facilities, relevant background on transportation of wastes, treatment of potential natural perturbation phenomena and safety assessment of anthropogenic impacts will be described.

(1) Waste transportation

Radioactive waste transportation from nuclear power plants, reprocessing plants, etc. is well established both domestically and internationally, with international standards and regulations such as those established by the IAEA [143] and additionally Japanese laws and regulations based on these.

Transport of waste to the repository surface facility from an interim store utilises dedicated transport casks. The technical standards and quality assurance plan of such transport casks are defined in the previously mentioned IAEA transportation regulations, based on extensive testing programmes - drops, fire, immersion, etc.

Both sea and land transportation (road and rail) are well established for long-distances although, if it is an option, exposure risk to the public is the lowest for marine transportation and this offers maximum flexibility for larger volumes of waste [144]. For this reason, preferred sites in the Nationwide Map (Section 1.3) are coastal locations and it is assumed that that marine transportation to a harbour near the repository site is followed by only local transfer on land.

Radioactive waste transport ships currently in use are designed for safety for all credible accidents, with double hull structures which are collision resistant, duplicate navigation systems, ship tracking systems using satellite communication, etc. [145]. Although transport casks for radioactive waste, specifications of transport vehicles, and transport routes are undecided at present, experience with SF and returned vitrified waste from abroad indicate that appropriate solutions can be readily developed as and when required (see Supporting Report 4-68).

(2) Managing natural perturbation phenomena

The risks of natural perturbation phenomena are strongly dependent on the geographical and geological setting of the site, which defines the design requirements necessary to assure safety. Some extreme natural phenomena can be excluded by siting, as listed in Table 3.1-1, including pyroclastic flows, lava flows, lahars, etc. Nevertheless, a range of natural phenomena that affect the safety of surface facilities must be assessed, such as earthquakes, tsunamis, landslides, floods, etc. as listed in Table 4.6-1, and appropriate safety measures implemented to reduce potential impacts, as is normal practice for sensitive structures [146].

As an example of this approach, design countermeasures for tsunami risks are illustrated in Figure 4.6-1. When locating sensitive facilities, the aim is to install them as high above sea level as possible.

Table 4.6-1 Safety measures for surface facilities considering natural perturbations

Natural perturbation	Safety measures (assuming effects constrained by appropriate siting)
Earthquake	Seismic design to ensure structures can withstand credible seismic forces
Tsunami	Utilise the topography of the area, e.g. installing key facilities as high as possible, setting protective seawalls, installing inundation prevention doors, etc. to withstand credible tsunami impacts
Flood	Utilise the topography of the area, e.g. installing key facilities as high as possible, installing inundation prevention doors, etc. to withstand credible floods
Wind (typhoon)	In consideration of the maximum wind speed observed around the site, the facility is designed to have sufficient strength to resist them
Tornado	The facility is designed not to be damaged by tornado wind pressure and impact load of flying objects
Freezing	Design based on the lowest temperature expected at the site
Precipitation	Design based on the maximum precipitation expected at the site. Establish a drainage plan to prevent flooding of buildings
Snowfall	In consideration of the maximum amount of snowfall expected at the site, the facility is designed to withstand credible loads
Lightning strike	Design lightning protection equipment to provide required protection
Landslide	In consideration of the observation records and the topographic and geological situation of the site, landslide countermeasures can be applied as needed
Volcanic effects	Even if at a distance from nearest active volcanoes, ash-fall must be considered with design to assure that credible events would not compromise facility safety
Biological effects	Design to exclude animals, e.g. exclusion nets used to prevent bat/bird entry of access shafts
Forest fire	Take protective measures if relevant, such as providing a barrier (fire break) between the facility and any surrounding forest

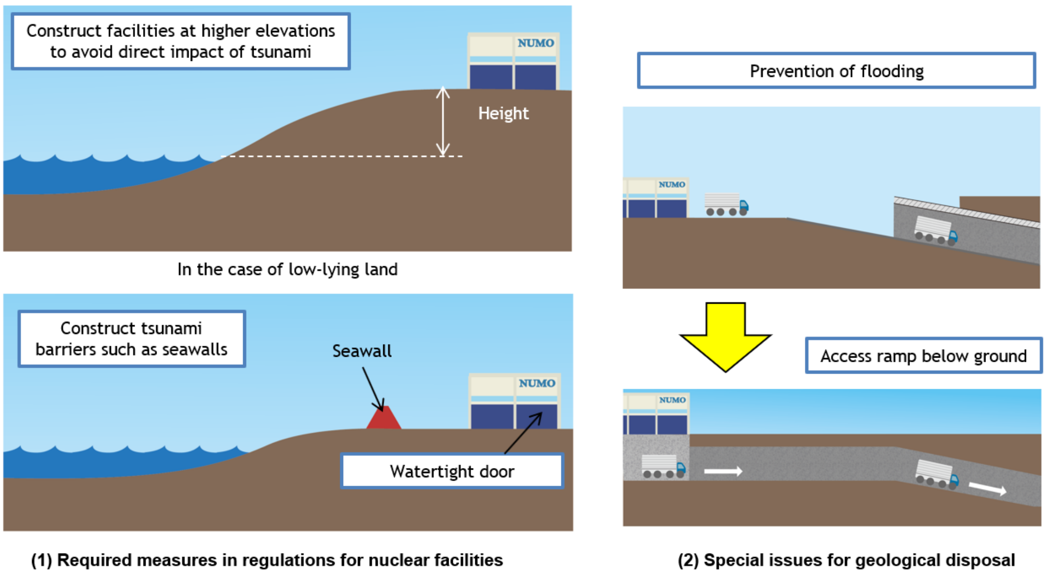


Figure 4.6-1 Illustration of tsunami countermeasures

If the tsunami risk is considered significant, it would be planned to take measures such as installing a seawall and installing robust doors to prevent inundation. Furthermore, in order to prevent a tsunami flooding the repository, as illustrated and discussed in Section 4.6.2 (4), the access ramp will be located at basement level of the surface facilities (i.e. underground – which will also avoid potential animal access). For other accesses to the surface, such as ventilation shafts, appropriate tsunami protection will be included in their design.

(3) Managing anthropogenic perturbations

Risks of anthropogenic perturbations depend on the geographical and social environmental conditions around the site, which defines the design requirements necessary to assure safety. Similar to the case of natural perturbations described above, appropriate safety measures are implemented to reduce potential impacts, as is normal practice for sensitive structures [146]: these are summarised in Table 4.6-2. It is recognised that this list is far from comprehensive (e.g. no consideration of climate change impacts, consequences of pandemics, etc.), but provides a starting point based on requirements to meet regulatory guidelines.

Table 4.6-2 Safety measures for surface facilities considering anthropogenic perturbations

Human perturbation	Safety measures
Aircraft impact	Structural design of sensitive facilities should account for largest credible impacts
Dam collapse	If this is a risk for a particular site, take safety measures as for tsunamis
Industrial explosion	Assessment of nearby industrial activities, evaluate risk from worst credible external explosion and assure sufficient separation from/protection of sensitive surface facilities
Industrial fire	Assessment of nearby industrial activities, evaluate risk from worst credible external fire and assure sufficient separation from/protection of sensitive surface facilities
Industrial release of toxic gas	Assessment of nearby industrial activities, evaluate risk from worst credible toxic gas release and assure sufficient separation from/protection of sensitive surface facilities
Industrial electromagnetic pulse	Assessment of nearby industrial activities, evaluate risk from worst credible electromagnetic pulse and assure sufficient separation from/protection of sensitive surface facilities
Shipping accidents	For coastal locations, a special concern is shipping accidents – especially if these could result in massive perturbations (e.g. oil tankers, LNG carriers, bulk ore carriers). Sensitive facilities should be located far enough away from deep water that they are protected from worst credible accidents
Illegal intrusion	Implement rigorous security measures against cyber terrorism. Implement rigorous access control, with additional measures to prevent intrusion into sensitive areas. This is complemented by walls/fences with intrusion detectors around the entire site, security patrols, etc. Off-site monitoring and close liaison with local authorities also allows any major threats (e.g. large demonstrations) to be identified well in advance and appropriate protection organised

In the case of prevention of impacts of illegal intrusion, the following characteristics of the waste are of relevance [147]:

- Waste is sealed in massive overpacks/waste packages that provide physical protection and make diversion of such material extremely difficult.
- Surface waste handling facilities are remotely operated, with strict control of access even for workers. They are also heavily constructed with massive concrete shielding, making perturbation from outside buildings very unlikely.

Based on these, the level of protection against illegal intrusion is considered to be even greater than that at nuclear power plants and other nuclear facilities and thus this could be classified as a “hard” target, with very low risk of any radiological hazard from such a perturbation [147].

Nevertheless, the nuclear industry recognises that cyber-security is a key issue for all sensitive infrastructure [148], and state-of-the-art systems would be a design requirement, not only at the time of construction but also as an ongoing need that would be managed by continuous performance review and updating of both hardware and software.

4.6.2 Design of waste reception, inspection and encapsulation facilities

The design of facilities for waste acceptance/inspection/encapsulation requires that the waste inventory and reference throughput are clarified for both HLW and TRU waste. In addition, since the natural and anthropogenic perturbations to be considered in the design of these facilities are so site-specific, designs presently focus on generic requirements for radiation shielding and containment.

The design of the surface waste handling facilities depends on the operational work flow, from first waste receipt to dispatch underground, constrained by key design requirements under normal operational conditions, such as the wall thickness necessary for radiation shielding and negative pressure management to assure containment of RNs in the event of accidents. Finally, designs will be refined to include countermeasures to respond to abnormal conditions, such as falls, fires and explosions.

(1) Configuration of facilities

The handling process for HLW and TRU waste starts with receipt of dedicated transport casks (as described in Supporting Report 4-68) containing the conditioned waste (see also Section 4.6.1(1)). After receipt, waste is moved to a controlled zone and removed from the transport cask, inspected, encapsulated in an overpack or waste package container (two different options for TRU waste considered) and then prepared for transport underground. For the PEM option, the HLW overpack and surrounding buffer are sealed in the handling shell under strictly controlled conditions. All such operations in the radiation-controlled area are rigorously monitored/electronically logged and tele-operated to the extent possible, which covers all normal operational conditions. Worker access is expected only for routine inspection and maintenance activities during breaks of operation, or as a result of specific perturbations – providing the basis design requirements for radiation protection.

(2) Waste inventory and throughput

As discussed in Section 2.1.1 (4), the Final Disposal Plan envisages emplacement of 1,000 HLW canisters per year for 40 years. HLW shipments in a dedicated ship are assumed to occur twice a year [149], in each case including 18 transport casks, each of which contains 28 HLW canisters. This defines the intake storage capacity for the temporary store [144]. After each transport cask is opened, 28 canisters need to be processed and this is balanced against the reference disposal rate of 5 overpacked canisters/PEMs per day by other buffer stores. These plans would be revisited and optimised as part of the iterative site-specific assessments to take placed during the LS, PI and DI stages.

The reference TRU waste inventory (90,584 primary containers with a volume of 19,018 m^3) [11] requires a disposal throughput of seven waste packages (mostly containing 4 but sometimes 2 primary containers) per day for 25 years [11]. The maximum loading of a transport ship is 3,000 tons, with 6 transports per year assumed. Table 4.6-3 shows the average quantity of TRU in each shipment, to serve as a basis for planning. As for HLW, these plans will need to be revised and optimised in the future.

Table 4.6-3 Reference shipment of TRU waste (6/year)

Primary waste container (waste group)	Number of transport casks	Number of primary waste containers per transport cask
Drum (Gr.3, 4L, 4H)	12	36
Canister (Gr.2)	8	28
Box container (Gr.4L)	1	2
Container for MHHRW (Gr.4H)	2	4
Drum (Gr.1)	2	8

(3) Design requirements

Top-level design requirements for acceptance, inspection and encapsulation facilities are given in Table 4.1-1, based on the interpretation of existing regulations and related legislation covering other nuclear facilities.

The requirements (safety functions) for operational safety focus on radiation containment and shielding, both related to radiation protection (see Table 4.2-1). Radiation protection is determined for both the public living near the site and all staff working in it. Under normal conditions, radioactive waste should be confined within designated radiation-controlled zones and associated shielding would ensure that doses received by personnel do not exceed the limits stipulated by law and, indeed, are ALARA. Radiation protection of the public and workers, and associated assurance of containment functions, are thus set as design requirements. In addition, regulations for nuclear facilities require provision of facilities to monitor radiation releases and exposure of workers while, as described above, it is necessary to monitor operations in order to identify and respond to any abnormalities.

As described in Section 4.5.6 for underground operations, abnormal conditions are also assumed in the design of the surface facility, including impacts, fires, explosions, loss of external power, etc., so preventing loss of safety functions in these cases is also set as a design requirement.

Further issues normally considered in relevant industrial operations that are not discussed further in this report are:

- As all waste handling is assumed to be remote control, even in abnormal conditions, associated radiation exposures to workers are not currently assessed (except for special tasks such as recovery).

- The impacts of natural perturbations described in Sections 4.6.1 (2) and 4.6.1 (3) are extremely site-specific and designs to reduce these are not considered at present.
- Designs will be required to withstand maximum expected seismic loading, but the calculation of credible seismic forces needs to be carried out based on the geological environment of a specific site and hence not assessed further at present.
- Prevention of illegal access, as described in Section 4.6.1 (3) is a requirement, but it is reasonable to consider only at a later stage of detailed design of site-specific facilities.
- Surface facilities providing conventional infrastructure and support services (e.g. administration, staff support…) will be examined at a later stage of detailed design.

In terms of radiation protection, as evaluated further in Chapter 5, design requirements to assure safety are summarised in Table 4.6-4.

Table 4.6-4 Operational safety design requirements

Design requirements	Function	Specifications
Radiation protection of the public	Shielding and other appropriate measures assure sufficiently low doses around the site	Facility installation layout, shielding walls, ventilation management, shielded transport cask
Radiation protection of workers	Shielding and other appropriate measures assure sufficiently low doses in controlled areas and other places where workers are present	Shielding walls, transport cask, limited access to radiation control areas
Ensuring radiation containment	Areas where radioactive contamination could occur are maintained under negative pressure	Radiation control area layout Ventilation and drainage systems (including filters/effluent management). Waste containers, overpacks, waste packages, transport casks
Radiation monitoring and measurement	Comprehensive monitoring of the containment function, automated alarm and response to any anomalies	Monitoring and measurement equipment, automated identification and response to anomalies
Prevention of functional loss in abnormal conditions	Designs include measures to prevent the occurrence of abnormalities and avoid loss of containment function even in abnormal conditions such as drops and impacts, fire, explosion, loss of external power and equipment failure	Nuclear standard, resilient design of structures, equipment and processes, including a philosophy of defence in depth to ensure safety for all credible perturbation scenarios

Table 4.6-5 outlines design requirements to ensure engineering practicality (based on general requirement noted in Table 4.1-1). Since the facility needs to be able to store all transport casks received in a shipment and then process these to provide packaged waste allowing the reference disposal rate, appropriate buffer stores and waste handling capacities are required. In addition, all operations in the radiation-controlled zone should be carried out by remote control (either strictly required due to high radiation or as commitment to keep worker doses ALARA), this is also set as a design requirement.

Table 4.6-5 Design requirements to assure engineering practicality

Design requirements	Function	Specifications
Capacity of buffer stores	Temporary storage of transport casks received in a single shipment and of waste containers during handling of the contents of a single cask	Layout/design of the waste handling facility
Waste package throughput	Ability to process waste package at a specified rate	Waste handling process plan, equipment design and maintenance plan
Remote control	All waste handling processes within the facility carried out by remote control, including routine maintenance and, to the extent possible, responses to abnormal conditions	Waste handling process plan, equipment design and maintenance plan, perturbation response plan

Finally, it should be again noted that the current plans will need to be revisited and optimised as part of the iterative site-specific assessments that will take place during LS, PI and DI stages.

(4) Design of waste handling facilities

(i) HLW

A schematic diagram of the HLW receipt, inspection and encapsulation facility is shown in Figure 4.6-2. As discussed further in Supporting Report 4-69, this includes a transport cask interim store and an inspection/buffer storage cell in which HLW canisters are removed from the transport casks and then those passing acceptance stored before overpacking. HLW canisters are inserted into the overpack and the lid welded in place within the overpack production and inspection room, where the seal performance is confirmed before transfer to the overpack buffer store prior to transport into the repository. As yet plans have not been developed for handling canisters or seals that fail acceptance criteria; this will however form a part of future R&D.

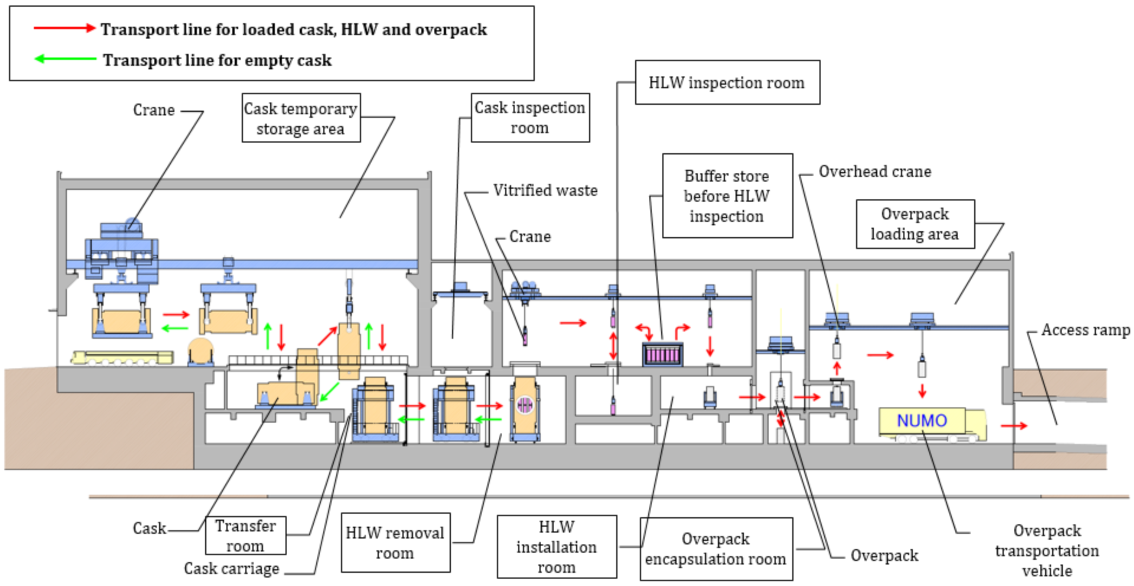


Figure 4.6-2 Schematic outline of the HLW receipt, inspection and encapsulation facility (H12V)

The size and layout of the waste handling line is set for a reference throughput of 1000 packages/year, giving a target of 5/day (see Section 4.6.2 (2)). For example, Section 4.4.1 (2) (viii) described the TIG welding method which takes about one day to weld a single lid and hence, assuming this option is chosen, 5 welding machines will be installed, with an additional spare to facilitate planning of maintenance and inspection. However, it should be noted that the target outlined here is only an example and decisions for the encapsulation facility have not yet been finalised. In addition, this schematic outline needs to be refined in the future in order to assess how required services are implemented (e.g. assuring sensitive areas are below atmospheric pressure).

After testing overpack seals, overpacks will be transported into the repository. In NUMO (2004) [2], the transport vehicle travels on the surface to the entrance of the access ramp, but this has been reconsidered to develop a design in which ramp access is directly from the basement of the waste handling building, as illustrated in Figure 4.6-3.

When this structure is adopted (discussed further in Supporting Report 4-70), it will be possible to both simplify the work flow and also provide protection from surface perturbations, especially those presenting a risk from flooding. It may also be possible for workers in radiation-controlled areas of the repository to evacuate to the surface through the access tunnel. A ventilation tower will be installed to ventilate the access tunnel independently of the waste reception, inspection and sealing facilities.

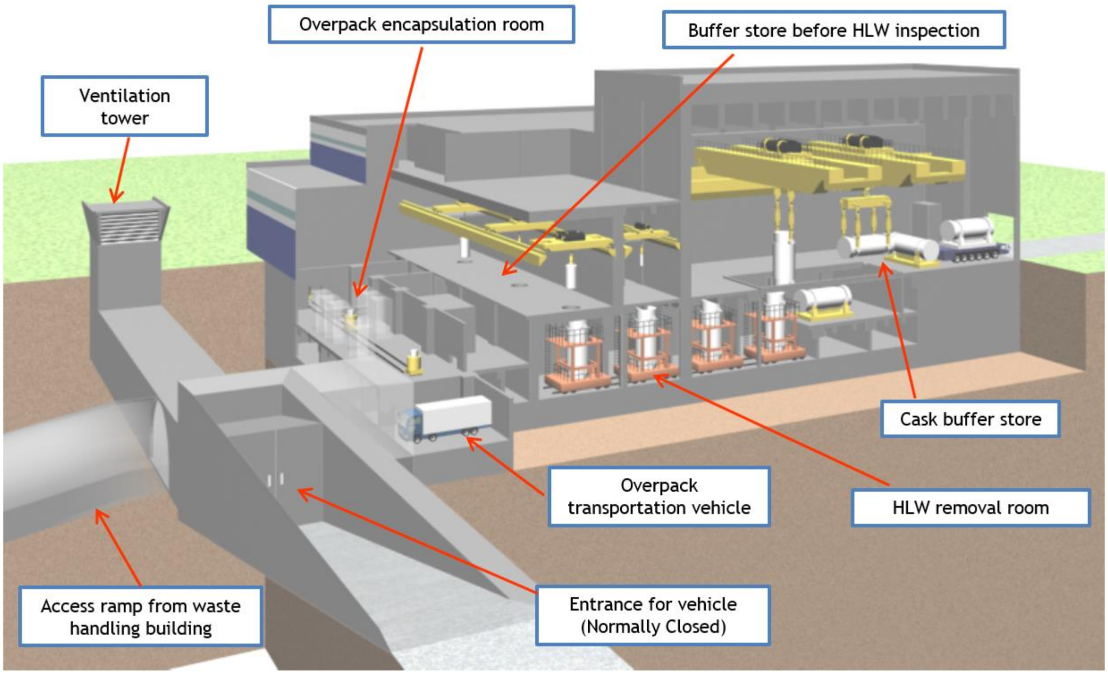


Figure 4.6-3 Illustration of the HLW receipt, inspection and encapsulation facility and its link to the access ramp (H12V)

Although the above was designed with the H12V concept in mind, for the PEM, the same facilities are used as far as the overpack production and inspection room. After this, as discussed in Section 4.4.1 (3) (v) (b), the overpack is remotely placed in compacted buffer within a steel handling shell in a PEM assembly cell (Figure 4.6-4) and then, after quality monitoring, placed in a buffer store until loading onto a transport vehicle for transfer underground [150]. Design of the PEM production line will be carried out in the future.

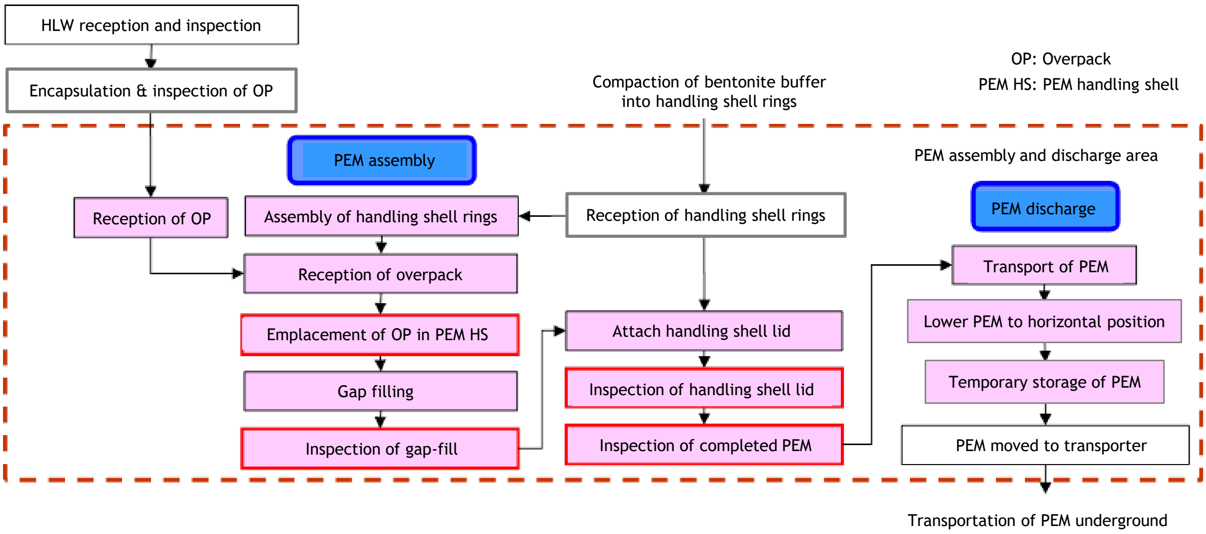


Figure 4.6-4 Flow diagram of PEM manufacture (Source: Kitagawa et al., 2013 [150])

(ii) TRU waste

A schematic diagram of the TRU waste receipt, inspection and encapsulation facility is shown in Figure 4.6-5. As discussed further in Supporting Report 4-71, this includes a transport cask interim store and an inspection/buffer storage cell in which TRU waste containers are removed from the transport casks and then those passing acceptance stored before packaging.

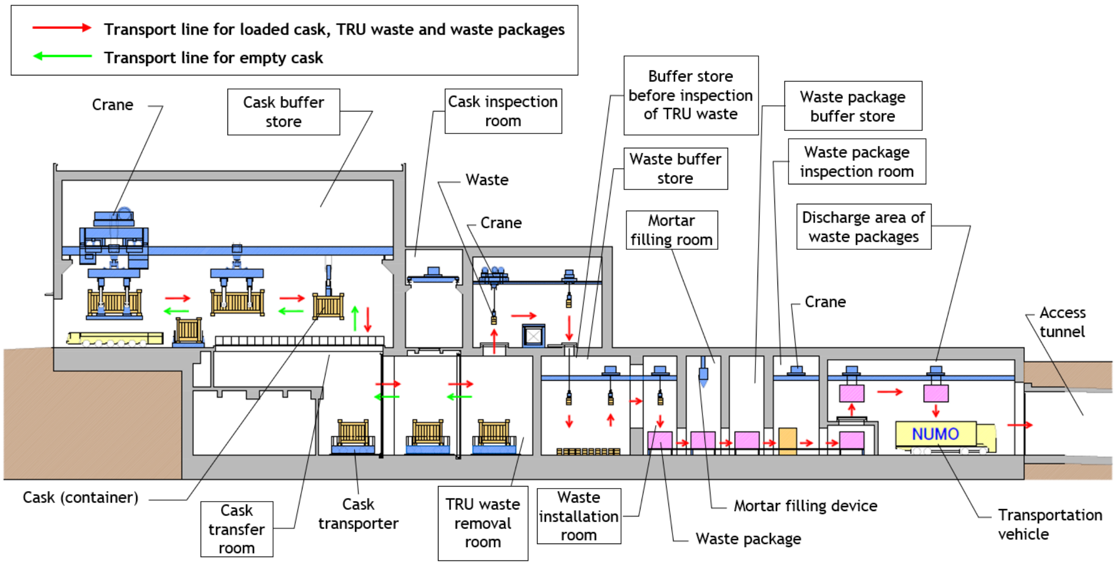


Figure 4.6-5 Schematic outline of the TRU waste receipt, inspection and encapsulation facility

Based on the throughput outlined in Section 4.6.2 (2), TRU waste containers are divided into different groups and are inserted into appropriate waste packages, which are infilled with mortar using a remote filler device. As curing of mortar takes about 3 weeks, the waste package is stored under controlled conditions during this time. It should be noted that, in regard to temporary stores, it has not yet been decided if the TRU waste groups will be stored together or if individual stores for each will be required. As waste groups will placed in identical waste package containers, a system of waste labelling and individual package tracking from receipt to final disposal will be required in any case.

In the case of waste package A, after inspection it is placed in a dispatch store prior to transportation underground. In the case of waste package B, after curing of the mortar, an upper lid is welded in place in the waste package production and inspection cell, then the seal performance is confirmed before transfer to the waste package buffer store prior to transportation underground. The direct connection from the waste handling building to the access ramp is also shown in Figure 4.6-3.

As for the HLW case, as yet the handling procedures in the case of waste/packages not meeting specifications have not yet been defined.

(5) Radiation protection assessment

For radiation shielding design (more details in Supporting Reports 4-72 and 4-73 for HLW and TRU, respectively), the effective dose received by workers under normal conditions should not exceed the limit defined in nuclear power reactor regulations (50 mSv over 1 year, 100 mSv over 5 years). Although the operations illustrated in Figures 4.6-2 and 4.6-5 are remote handled, workers will spend time in surrounding areas, with the type of work involved used to derive criteria for design dose rate targets and hence required shielding thickness.

For general public in the vicinity of the facility, in addition to shielding in the waste handling facility and that provided by surrounding buildings, the distance to the site boundary reduces doses and should ensure that they are below values specified in regulations (limit 1 mSv/y, target 50 μSv/y). The assessment to confirm this is outlined in Section 5.3.

The containment of radioactivity is assured by transportation casks, waste canisters/containers and overpacks/waste packages. Even in the case of surface contamination (identified during acceptance inspection) or releases due to a fall during handling (described in Section 4.6.2 (6) (i)), negative pressure in the facility and ventilation/drainage management will prevent any releases from the radiation-controlled areas.

(i) HLW

Table 4.6-6 lists as examples the calculated shielding thicknesses for the transport cask buffer store and the HLW inspection and buffer storage cell, assuming shielding walls of reinforced concrete, with details given in Supporting Report 4-72.

Table 4.6-6 Required shielding thickness for HLW handling areas

Structure	Transport cask buffer store (m)	Waste inspection/buffer storage cell (m)
Wall	0.60	1.3
Floor	0.65	1.3
Ceiling	0.35	1.2

After entry of the transport cask into the facility, all operations occur by remote handling under negative pressure and strictly managed ventilation/drainage discharges. In addition, radiogenic heat from the transport cask temporary store is designed to be removed by natural convection, like existing interim stores. However, HLW in internal buffer stores is cooled by active ventilation, as needed due to the negative pressure control.

The above are the results of a study for H12V, but the process up to overpack encapsulation is common for the PEM and, thereafter, there is no need for additional radiation protection measures.

(ii) TRU waste

As for HLW, Table 4.6-7 lists as examples the calculated shielding thickness for the TRU waste transport cask buffer store and the waste inspection and buffer storage cell, assuming RC shielding walls (details in Supporting Report 4-73).

Table 4.6-7 Required shielding thickness for TRU waste handling areas

Structure	Transport cask buffer store (m)	Waste inspection/buffer storage cell (m)
Wall	0.75	1.25
Floor	0.65	1.20
Ceiling	0.35	1.15

The basis for assuring containment of radiation during handling is the same as for HLW, although here heat production is not a concern.

(6) Examination of safety in the event of perturbations

(i) Drops

For transport casks, their design resistance to high energy impacts ensures that they are effectively immune to any drop that might occur during their handling. Drops would be further prevented by operational procedures, barriers, warning lights and sounds, etc.

For HLW, lifting and moving of the transport cask, the HLW fabrication canister, the overpack and the PEM is by gantry crane (Figure 4.6-2); therefore, the same measures introduced to prevent accidents from such lifts underground are directly applicable (see Table 4.5-34). If drops occur, consequences can be minimised by limiting the lifting height and providing impact limiters on surfaces onto which such falls could occur.

The most vulnerable unit lifted is certainly the HLW canister although, based on previous studies [151] [152], it has been confirmed that, even for drops from a height of 9 m, the stainless-steel container only deforms and there is no loss of integrity. For this reason, although the facility is designed to limit the lifting height to the minimum practical, an absolute limit of 9 m is specified. Although they are certainly more robust, lifting height limits for all other units are also set to 9 m. In addition, where practical, drop limitation and impact reduction measures are incorporated into the designs.

For TRU waste, the situation is very similar to HLW with the key difference being the robustness of the various primary waste containers. Amongst these, drums (Gr.1, Gr.3, part of Gr.4L) have been subjected to drop tests from heights of up to 9 m. For heights up to 6 m drums are deformed without loss of integrity but, above this, drum lids may burst or penetrative cracks may occur [153]. It is possible that measures could be implemented by the waste producer to tailor infill (robust concrete or surface bitumen coating) so that RN release risks can be minimised even in the event of drum containment failure.

For Gr.2 wastes (in a canister similar to that for HLW), there is again evidence that integrity is not lost even when dropped to a rigid floor from a height of 9 m [154]. Box containers for waste assigned to medium depth disposal are similar to those used for Gr.4L waste; drop tests of these from heights of up to 9 m show deformation and penetration cracks occur, but no loss of containment [76] [78].

Although lifting heights are always minimised, based on these results, an absolute drum lifting height is set as 6 m, while that for box containers is 9 m. Although there is no specific evaluation for MHHRW containers, the lifting height limit for drums is assumed until further evidence is available.

Handling of the waste package assumes movement within the facility by conveyor, but, when loading onto the transport vehicle, waste package A is lifted by a forklift and waste package B is lifted by gantry crane. The handling height of the forklift depends on its lifting capacity, but will be around the height of the platform of the transport vehicle (about 2 m). Although lifting heights by the gantry crane could be up to 8 m, these will be strictly controlled to ensure that they are at the minimum needed and cannot exceed defined limits.

(ii) Fires and explosions

The concept of fire prevention is fundamentally the same as that outlined in Section 4.5.6 (2) for the underground facilities, focused on limitation of the presence of flammable materials and their substitution by flame-retardant or non-combustible alternatives to the extent practical (details of flammable materials present and fire prevention measures are given in Supporting Report 4-74). With current technology, fire risk cannot be completely eliminated and hence fire detection equipment, alarms and fire extinguishing equipment (remotely operated when feasible) will be provided to minimise consequences. In addition, surface facilities will include a fire brigade, with a particular responsibility of ensuring that fires outside radiation-controlled areas are quickly controlled and cannot spread to more sensitive areas.

For TRU waste, Gr.3 bituminised nitrate does not fall under the designated flammable substances specified in the Fire Service Act, but spontaneous ignition is possible under some conditions, particularly following biodegradation if this occurs during storage prior to disposal. In order to minimise risks, Gr.3 buffer stores (incorporating appropriate fire extinguishing equipment) will be separated from those handling heat-generating waste by fireproof barriers, such as concrete walls, steel fire-doors, etc.

No credible explosion risk has been identified to date for HLW, but the moisture in the mortar filling for TRU waste generates hydrogen gas due to radiolysis; or hydrogen/methane could result from either radiolysis or biodegradation of bitumen. Therefore, to reduce explosion risks, countermeasures as shown in Table 4.5-24 would be implemented, including explosive gas monitoring and backups to ventilation (e.g. catalytic combiners). If any specific waste is assessed to present a significant explosion risk, options to reduce the quantity of explosive gas that can be produced by changing waste conditioning materials or procedures, or even reconditioning waste, could be considered. Nevertheless, pros/cons and cost-effectiveness of any such measures need to be carefully assessed, taking into account all aspects of waste production/conditioning/packaging, handling, storage, transportation and disposal.

(iii) Loss of external power

Within the nuclear industry, "uninterruptable" power supplies are standard for safety-critical operations so that, if normal power supply is lost, local backups (batteries, generators, capacitors, etc.) provide enough electricity for operations to be brought to a safe shutdown. This is complemented by failsafe designs that, even with complete loss of power, default to an inherently stable situation (e.g. crane grips for waste packages that require power for opening rather than closing, lifting mechanisms that lock in place on power loss or use mechanical relaxation to return to a stable state). In general, surface facilities would be inherently more resilient to such power loss than those underground.

(iv) Common mode failure

Any facility located on the surface is vulnerable to perturbations that can give rise to common mode failure (CMF): the coupled collapse of many of the barriers providing defence in depth. The initiating events are inherently impossible to describe in detail, but examples directly impacting surface facilities would include large earthquakes accompanied by tsunamis (as for Fukushima Daiichi), a major volcanic eruption with a huge ash fall (e.g. Mount St. Helens) or a national/regional socio-political collapse (e.g. as a result of worst-case global warming), all potentially leading to long-term loss of external services and also damage to structures and services on site. As noted above, the heavily engineered structures of safety-critical buildings, fail-safe design and extensive on-site service back-ups make the surface facilities inherently more robust than most other nuclear or industrial facilities. Nevertheless, a more detailed assessment of credible scenarios and, if required, adoption of required countermeasures will be carried out after candidate sites have been identified.

On a smaller scale, failure of key equipment (or operator error) can lead to cascades of impacts. As for the case underground, when such scenarios are identified, special efforts must be made to provide defence in depth in terms of the initiating event, reducing probability of occurrence to the extent possible and providing countermeasures to reduce consequences if it does occur (as explicitly required by nuclear regulations).

4.7 Reversal and retrieval

As described in Section 2.3.3 (1), a design requirement is that emplacement processes can be reversed and waste retrieved if required [155]. This presents potential conflicts with pre- and post-closure safety requirements, so that the following can be distinguished:

- Reversal – stopping the waste handling/emplacement process at any time (usually as a result of an operational problem or failure of QA) and, with the equipment available, returning it to an appropriate store until a decision on future management is made.
- Retrieval – recovery of some or all waste that has already been emplaced, which will generally require special equipment and handling depending on the reason for retrieval.

Thus, reversal is a requirement that is built into the design process and is a consequence of a rigorous QA system, while retrieval – which is always possible in principle – is assessed from the point of view of practicality with existing technology, at least up to the point of repository closure. This section focuses only on ease of retrieval; reversibility will be assessed in more detail after concepts are developed for specific sites. The ease with which waste retrieval can be carried out will, of course, depend on the reason for waste recovery and how far the emplacement activities have proceeded at that time.

4.7.1 Assuring practicality of retrieval

Issues associated with waste retrieval depend on the stage of repository operation, and it is internationally recognised that the complexity and hazard of the process increases as the stage of operation progresses [155]. Thus, in order to examine the technical practicality of specific retrieval methods, it is necessary to first understand the state of the EBS at the time of recovery. The following summarises the results of investigations for H12V, PEM and TRU waste.

(1) HLW

(i) H12V implementation

Based on the simple sketch in Figure 4.2-6, the evolution of repository implementation was classified into three states, as shown in Figure 4.7-1 (specifically for H12V).

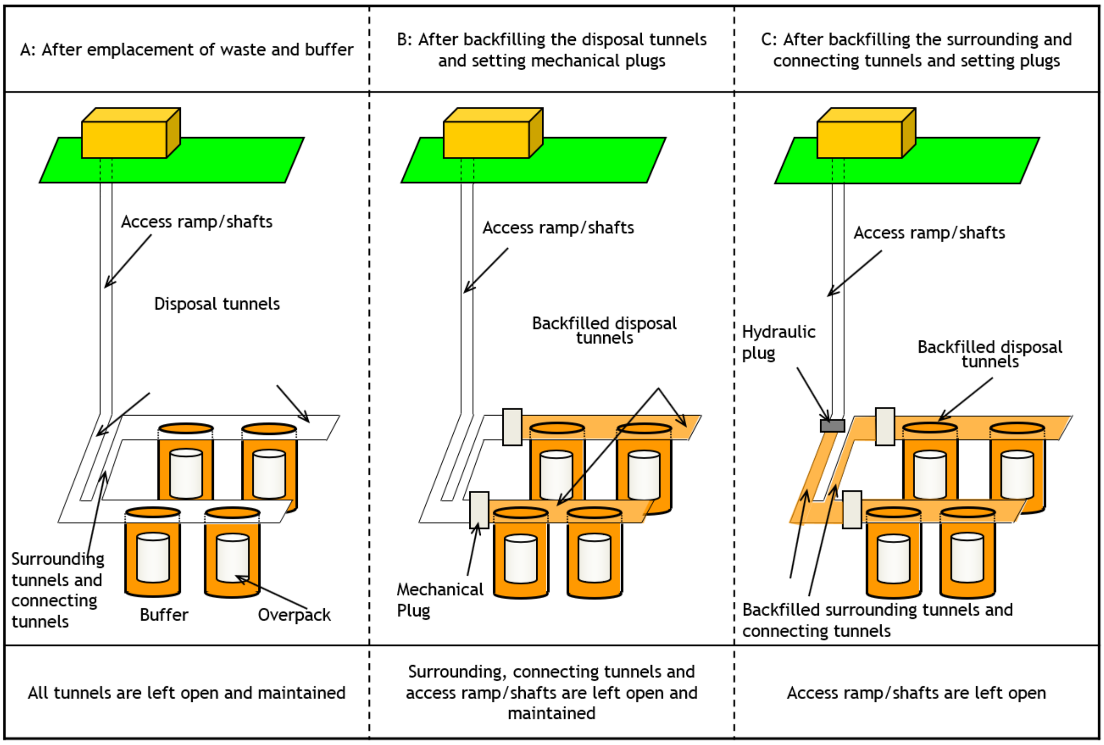


Figure 4.7-1 Stepwise increase in retrieval challenges (H12V)

Figure 4.7-1 is extremely simplistic, but illustrates general increase in difficulty of waste package recovery as work progresses. In the simplest case A, the overpack and buffer are emplaced, but the disposal tunnel is not backfilled. In B, the disposal tunnel has been backfilled and the plug emplaced, although access to the disposal panel is still open. In C, all connecting tunnels have been backfilled and additional plugs emplaced, so that only the access ramp/shafts are open.

(ii) PEM implementation

For the PEM, the equivalent three states are shown in Figure 4.7-2. A is then the case where PEM is placed in the disposal tunnel and ease of recovery is assured as no backfilling is present. In practice, it may be that backfilling would be easier done in a stepwise manner as the PEMs are emplaced but, even in this case, recovery is relatively easy before the plug is emplaced.

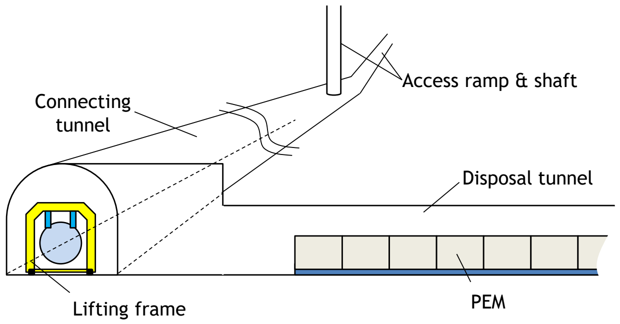
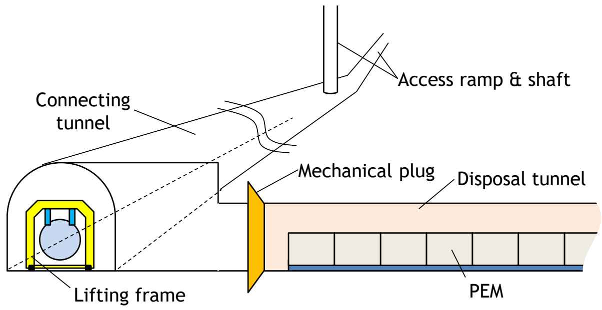
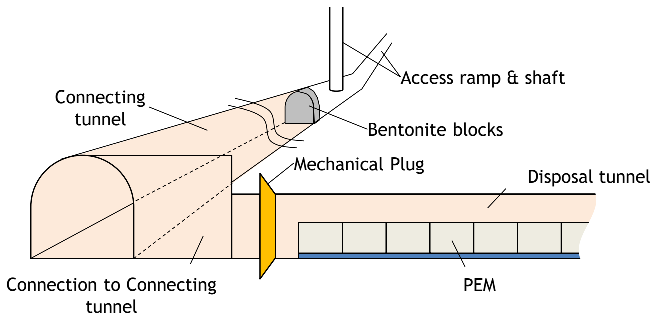
<table>
<tr><td>A:
After PEM installation</td><td>
</td><td>After PEM emplacement</td></tr>
<tr><td>B:
Disposal tunnel backfilling/construction of mechanical plugs</td><td>
</td><td>Open connecting tunnel after disposal tunnel backfill and mechanical plug emplacement</td></tr>
<tr><td>C:
Connecting tunnel backfilling and installation of hydraulic plugs</td><td>
</td><td>Open access tunnel after connecting tunnel backfilling and hydraulic plug emplacement</td></tr>
</table>

Figure 4.7-2 Stepwise increase in retrieval challenges (PEM)

In B, the disposal tunnel is backfilled and the mechanical plug installed, but the open connecting tunnel will ease retrieval. For C, the connecting tunnel is backfilled and the hydraulic plug emplaced, with only surface access open to aid retrieval.

(2) TRU waste

Fundamentally the same three states can be seen for TRU waste (Figure 4.7-3): A after waste emplacement and infilling/buffer emplacement but with vaults still open; B after vault backfilling and plugging and C after backfilling and plugging connecting tunnels.

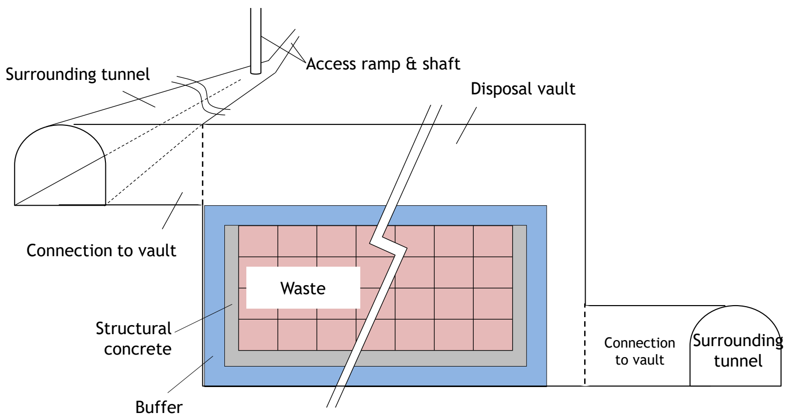
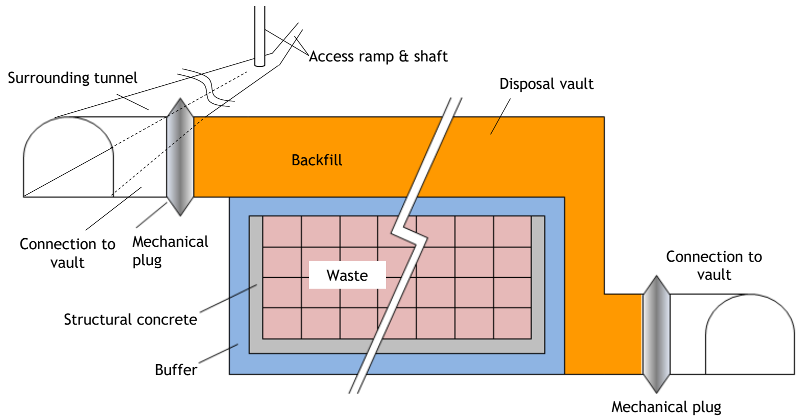
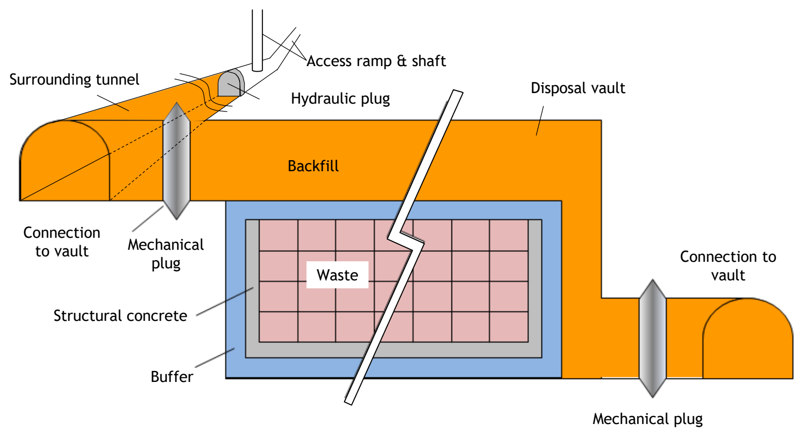
A: Waste emplacement along with any infill/backfill		Disposal vault open
B: Disposal vault backfilled and mechanical plugs emplaced		Connecting tunnel open
C: Connecting tunnel backfilled and hydraulic plugs emplaced		Only surface access open

Figure 4.7-3 wise increase in retrieval challenges (TRU waste)

(3) Retrieval issues for different operational states

The following is a summary of the issues associated with retrieval for different operational states and waste disposal options:

- A state: PEMs can be retrieved by simple reversal of emplacement process, but H12V and TRU waste need special equipment to retrieve waste packages from holes/vaults.
- B state: in all cases mechanical plugs and disposal tunnel/vault backfill must be removed before the actions required in A.
- C state: in all cases hydraulic plugs and connecting tunnel backfill must be removed before the actions required in B.

Some key issues associated with such retrieval for EBS components and the surrounding host rock are illustrated in Table 4.7-1 for the specific case of H12V. Here the assessment of impacts focuses on consequences if operations are modified to extend the A, B or C cases to maintain ease of retrieval, as opposed to the reference case of backfilling/plugging as quickly as possible. An additional issue not yet assessed is what to do with recovered waste packages, as their integrity may have been compromised. This will be a topic for future work.

Factors concerned with maintaining retrievability		Case A	Case B	Case C
Ease of retrieval	Number of steps for retrieval	① Removal of buffer ② Retrieval of overpack	① Removal of mechanical plug ② Removal of backfill ③ Remove of buffer ④ Retrieval of overpack	① Remove of hydraulic plug ② Removal of backfill in connecting and surrounding tunnels ③ Removal of mechanical plug ④ Removal of backfill ⑤ Remove of buffer ⑥ Retrieval of overpack
	Cost for retrieval	Low ←→		High
Impact to host rock in the near-field	Lowering of groundwater level	Wide range ←→		Small range
	Water velocity in near-field	Fast ←→		Slow
	Redox potential in near-field	Aerobic ←→		Anaerobic
Impact to EBS	Risk of piping erosion of buffer	High ←→		Low
	Risk of aerobic corrosion of overpack	High ←→		Low
Maintenance of tunnels	Maintenance items	Disposal, surrounding, connecting and access ramp & shaft	Surrounding, connecting and access ramp & shaft	access ramp & shaft
	Water drainage	Large ←→		Small
	Maintenance cost	High ←→		Low

Table 4.7-1 Relative ease of retrieval and impacts for different states (H12V)

The complexity of the recovery procedure and the associated costs and hazards increase in the order A < B < C as described above. The recovery tasks considered to require remote handling from the viewpoint of radiation protection of workers are mainly associated with removal of waste and the surrounding EBS components.

In terms of the influence of the near-field host rock, the extent to which the groundwater table is lowered and water chemistry is changed depends on the rock and site conditions as well as the period of time that tunnels have been open. Continuing drainage to maintain ease of recovery may affect hydrogeological characteristics and, in some cases, long-term safety after closure, with the impact considered to increase in the order of C < B < A.

With regard to the effects on engineered barriers, in the case of H12V and TRU waste including a buffer, during state A buffer will take up water and swell, making it difficult to maintain EBS quality. In addition, for state A, with time, loss of buffer due to piping erosion and the amount of corrosion of the overpacks/waste packages by air both increase, making it preferable to reduce the duration of this state to the extent possible. The influence becomes larger in the order of C < B < A. In the case of the PEM, the carbon steel handling shell corrodes when exposed to air but, as long as it maintains its integrity, the contained buffer will not swell.

With regard to the impact on tunnel maintenance, if tunnels are kept open for long periods of time, deterioration of the lining/support system as well as on the long term EDZ properties have to be considered and regular inspection and maintenance will be needed (with potential complications if this is in a radiation-controlled zone).

To assess ease of retrieval, it is necessary to evaluate such issues in a comprehensive manner but, at the present time, focus is on the B state to illustrate how these might be handled.

4.7.2 Retrieval methods

The recovery method according to the different options in state B is considered, illustrating the development status of the related recovery technology.

(1) HLW

(i) H12V

The recovery process is initiated by removal of the mechanical plug, assumed to be made of reinforced concrete (see Section 4.5.3 (2) (ii)), using heavy machinery such as a remote handled hydraulic breaker. Then the backfill, assumed to be a bentonite-rock mixture (Section 4.5.3 (1) (ii)), can be removed by equipment such as a remotely operated backhoe.

Since overpack corrosion during the period of maintaining recoverability, i.e. in the order of 40 years according to current plans, can be confidently assumed to be limited, it is possible to recover the overpack intact. Here, when removing the buffer, care must be taken not to damage the overpack. Therefore, to avoid risks associated with over-coring [1], a technique using brine flushing has been developed [156] (Figure 4.7-4) that removes buffer in the form of a slurry.

(a) Prototype of buffer removal device **(b) Buffer removal test**

Figure 4.7-4 Demonstration of buffer removal by brine flushing ((a) [119], (b) [158])

With regard to this technology, tests have been conducted in international [157] and domestic facilities [119] [158], including using a remote controlled, full-scale device, and hence basic practicality can be assured, even if more specific technology for this, coupled to associated lifting of the overpack, would need further development before they could be applied under repository conditions.

(ii) PEM

For the PEM system, removal of the mechanical plug is as for H12V, so focus is on methods of removing backfill and recovering the PEM as a unit (details are given in Supporting Report 4-75). The clearance between the PEM and the bedrock/liner is relatively large, so when rock conditions allow, most of the backfill could be removed by a road header, and then, so as not to damage the PEM handling shell, thereafter using brine flushing to remove the rest (see Figure 4.7-5).

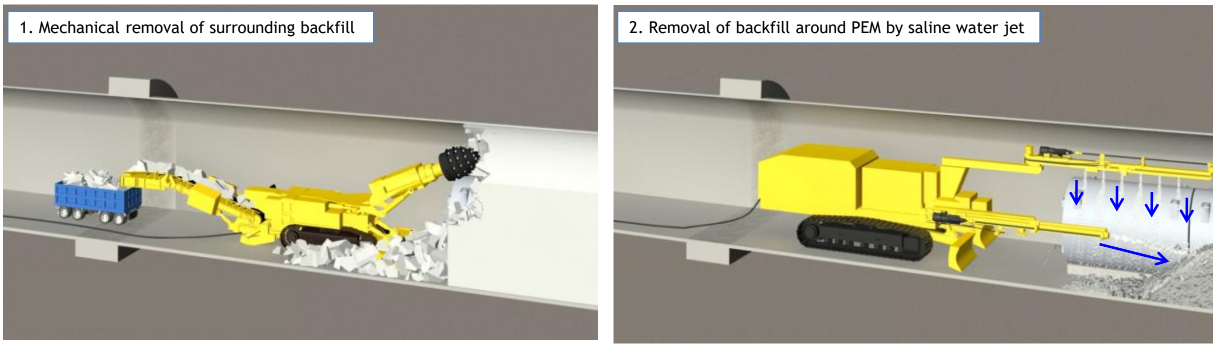


Figure 4.7-5 PEM backfill removal (Left: using road header; Right: brine flushing)

After removing backfill, a recovery device will enclose and lift the PEM from its pedestal (Figure 4.7-6).

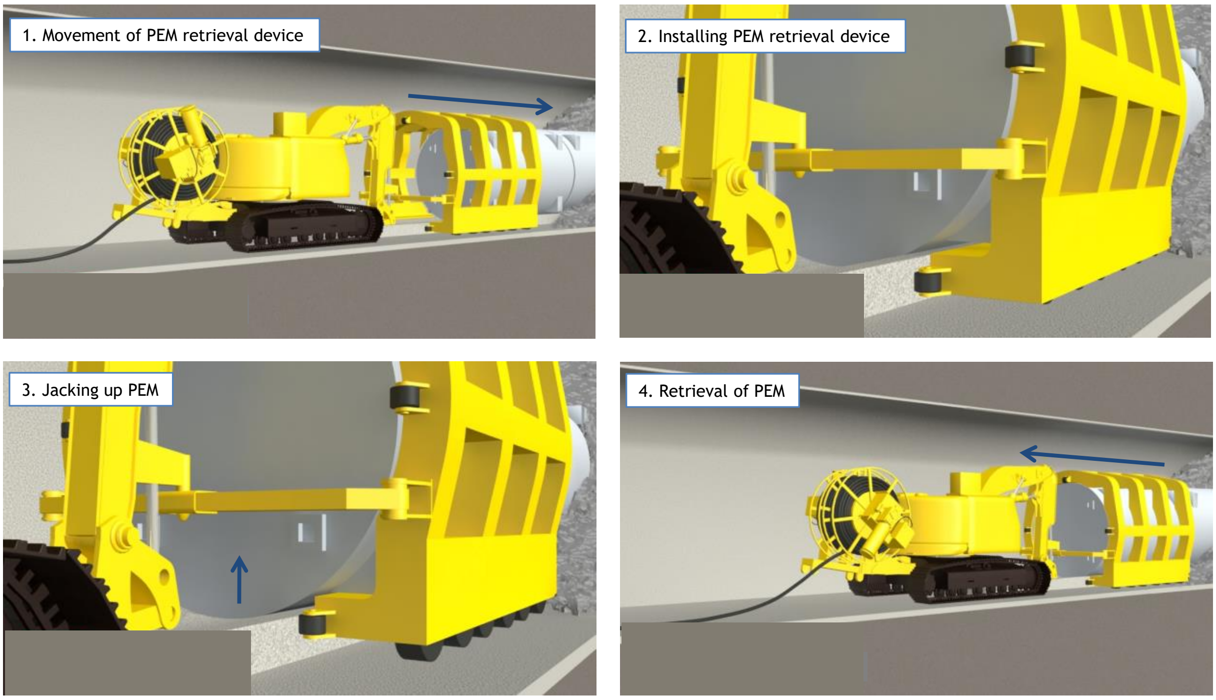


Figure 4.7-6 PEM recovery

This particular method allows PEM recovery as a unit, even if the mechanical strength of the handling shell or lifting points cannot be assured. Also, even if not strictly required, this can be implemented by remote control to keep worker doses ALARA.

(2) TRU waste

In order to carry out the recovery work safely and efficiently, it is desirable that waste packages are structurally sound and that the function of containment is assured for both waste packages A and B.

As illustrated in Figure 4.7-3, in state B the initial removal of a mechanical plug and overlying backfill is effectively as for H12V. Options thereafter are either excavation of infill from the top (assumed left-hand plug in Figure 4.7-3 removed) or from the side (assumed right hand plug removal). The choice between these may depend on the type of waste package, as waste package A is designed to be lifted from below by a forklift, while waste package B is lifted from the top by a crane – although it is not clear that the associated lifting features will be accessible after infilling.

Since the waste packages contain, and are surrounded by, cementitious infill, any porewater present will be highly alkaline, so the corrosion rate of the carbon steel waste package can be confidently assumed to be very small (1 μm/y or less) [80], and therefore any degradation due to corrosion is considered to be negligible. Currently, the remote-handled technology to remove the hardened infill without damaging the waste package and then extract the waste package does not exist, so future technological development is necessary. From this point of view, it may be useful to consider disposal concepts that do not fill gaps between waste packages, as shown by ANDRA [111].

4.8 Summary and future perspective

4.8.1 Summary

Chapter 4 has outlined repository concepts and designs tailored to the three SDMs, based on depths of 500 m or 1,000 m depending on rock strength. Key results are summarised below.

(1) Repository design method

Repository design is based on specific design requirements that ensure safety as well as engineering practicality and economic rationality. By applying this method during stepwise site selection, it is possible to iteratively refine repository design so that it can ensure the required safety functions while flexibly responding to evolving geological environmental and socio-political boundary conditions.

(2) HLW EBS

The HLW EBS components are taken over from H12 and, for the 3 reference SDMs, assessed to check that all design requirements were met. In particular, as a result of work carried out since the H12 report, the specified 190 mm thickness for the carbon steel overpack has been shown to have the potential to assure its containment function for at least 17 ky after closure, exceeding the design requirement of preventing contact of groundwater and HLW for 1 ky. However it should be noted that a more careful assessment will be needed in the future before full credit for this containment time can be assured. Therefore, depending on the geological environment of the site, it is considered possible to reduce overpack thickness in the future. In addition, the reference buffer is known to have reduced swelling performance in high salinity groundwater, but specifications have been developed to ensure the required performance (e.g. assuring diffusive solute transport, acting as a colloid filter) for a relevant range of salinities. Furthermore, because the buffer provides mechanical protection, its stability has been demonstrated so that key safety functions (e.g. protecting the overpack from earthquake impacts) can be assured for relevant timescales.

Of the disposal options, practical construction of the reference H12V EBS is feasible only under conditions of low humidity and low water inflow into disposal holes. Otherwise, countermeasures to prevent perturbations resulting in buffer density loss must be implemented, which have not been fully developed as yet. For the PEM, EBS emplacement is less problematic and, although this has been less well studied, demonstration including in-situ tests in URLs are ongoing in Japan and abroad. In the future, based on the conditions found at actual sites, alternative disposal concepts or EBS construction methods may be considered.

(3) TRU waste EBS

Based on TRU-2, two waste package options have been considered. Both are made out of steel, with cementitious infill, but one is thinner-walled and without a lid (designed for lifting by a fork lift) while the other has thicker walls and a welded lid (designed for lifting by a crane). The latter also provides an assured containment time of about 300 years after closure.

The EBS also includes a buffer to reduce the release and migration of long half-life, mobile RNs, such as I-129 and C-14, present in waste Grs.1 and 2. It was also decided to install a buffer due to the possibility of thermal deterioration of vault infill for relatively high thermal output Gr.4H. The buffer material has long-term mechanical stability and, despite interactions with hyperalkaline cementitious leachate, the specification ensures that the expected safety functions can be maintained for a sufficiently long time.

(4) Design of underground facilities

For the design of the underground facilities, a method of laying out the disposal panels was developed to take into account the distribution of Layout Determining Features (LDFs) in the 3 SDMs and ensure that there are no problems with excavation of tunnels and construction and QA of the EBS. Furthermore, preliminary Emplacement Determining Factors (EDFs) have been suggested, but it is noted that these would be very host rock, site and repository concept dependent and, thus, will be better specified in the future. The post-closure safety aspects of such layouts will be assessed in Chapter 6 and, in the future, will provide feedback that will be reflected in design refinement. In addition, design requirements were set so that radiation protection and general occupational safety are assured by the layout of connecting tunnels and access ramps/shafts. In particular, work flow lines and ventilation/drainage routes were organised so that the construction and operational zones are separated, with independent provision of key services.

After repository closure, it is necessary to prevent tunnels acting as short-circuit transfer routes for RNs. For this purpose, hydraulic plugs are installed at key locations and tunnels backfilled with a low permeability bentonite-crushed rock mixture.

Multiple safety measures to minimise probability and consequences of abnormal conditions (drops, fires, explosions, loss of external power and even CMF) were also developed, with particular reference to experience overseas. In case of any perturbation that could lead to loss of the containment function, measures are developed to prevent radiation releases outside of the facility in either ventilation or drainage. These safety measures will become more specific as detailed design of underground facilities for the geological conditions at actual sites proceeds.

Required construction technology is generally available and proven in major projects, such as the construction of underground power plants. The technology for backfilling and plug construction is currently at the stage of equipment development, with demonstration tests at full scale, using underground research institutes, already well advanced in Japan and overseas.

(5) Design of surface facilities

In this report, transportation of waste to surface facilities is considered in order to evaluate logistical constraints on waste handling. There is wide experience in Japan of such transportation and, for a coastal location, marine transportation of both HLW and TRU waste has demonstrated safety and allows for efficient movement of the relatively large inventories of waste involved.

Design to date has focused on the most sensitive facilities, which directly handle waste from the point of its receipt to dispatch underground for disposal. Standard nuclear industry guidelines ensure radiation protection of workers and the general public from all normal operations and credible perturbations. In the design, selecting locations for the installation of such facilities and their structural design is based on safety measures to reduce risks from natural perturbating phenomena.

For receipt, inspection, and encapsulation/packaging facilities for HLW and TRU waste, design includes specification of wall thicknesses to provide sufficient radiation shielding and safety measures to ensure containment of RNs in case of perturbations. It has been shown how multiple safety measures can prevent the loss of containment even in the abnormal conditions (drops, fires, explosions, loss of external power and CMF), complementing working under reduced pressure with careful management of ventilation and drainage. These safety measures will become more specific as the detailed designs for the geological and social conditions of specific sites proceeds.

(6) Assuring retrievability

Maintaining the option to easily retrieve waste after emplacement tends to conflict with other requirements to assure both pre- and post-closure safety (and also reduction of costs and environmental impact), so the trade-off of increasing effort for retrieval has to be accepted to allow stepwise stabilisation and isolation of disposal and connecting tunnels. The greatest challenges are associated with the remote-handled removal of the waste from disposal tunnels/vaults. The practicality of HLW recovery has been confirmed by technology demonstration tests at large/full scale and in-situ in URLs. Although it is considered possible to recover TRU waste using existing civil engineering technology, detailed design and demonstration of practicality will be needed in the future.

4.8.2 Issues for specific geological environments

In addition to the generic points above, specific points for the three representative host rocks considered and those for the special case of disposal under the coastal seabed are summarised below.

(1) Plutonic rocks

For plutonic rocks, it is particularly important to note that the frequency of water bearing fractures in the reference SDM is high and the amount of inflow into tunnels could be greater than for the other host rocks. In particular for the H12V option, it is considered that humidity control in disposal holes during installation of buffer and overpack will be difficult. In this case, it is also necessary to decide if disposal holes are practically unusable. As a result, the proportion of usable disposal holes may decrease, thus requiring more reserve volume than for the other representative host rocks.

The strength of the rock is good from the viewpoint of assuring mechanical stability of tunnels and the repository can be located at greater depth than in the case of softer rocks. However, at greater depths, in order to provide suitable working temperatures, it may be necessary to take operational measures such as cooling ventilation air.

(2) Neogene sediments

Neogene sediments have relatively low strength and shallower disposal/more extensive tunnel support may be required compared to stronger rocks. For H12V, in order to assure stability, a larger waste emplacement pitch is needed compared to the other host rocks and the required footprint is much larger than that for the PEM option. In addition, since the TRU waste vaults have a relatively large cross section, a complex excavation/support process is required in order to assure the required mechanical stability.

Since some Neogene sediments are considered to have a relatively high risk of containing methane, as noted in Section 4.5.6, special protection measures in terms of monitoring, ventilation and explosion-proofing of equipment may be needed.

The frequency of fissures and faults in the SDM is relatively small, as is the amount of groundwater inflow, so quality control of emplaced buffer and materials is relatively easy.

(3) Pre-Neogene sediments

The characteristics of the Pre-Neogene sediments are close to those of plutonic rocks and hence the comments in (1) above apply here. In addition, in the case of Pre-Neogene accretionary complexes, to design a repository layout in accordance with geological structures such as folding and LDFs, a DET layout was chosen to provide more flexibility to change the length of disposal tunnels compared to TT layouts.

(4) Sub-sea disposal

Discussion in this chapter does not explicitly specify whether the disposal footprint lies under land or sea, although the hydraulic gradients derived from the SDM imply that it is under land. Nevertheless, for preferred coastal locations specified in the Nationwide Map, there may be advantages in sub-sea disposal.

Sites located below the seabed but accessed from land are not precluded by international agreements constraining use of the sea and have the potential advantage of very low hydraulic gradients and also being less affected by future climate change. The layout of the repository shown in this chapter assumes access by shafts and a ramp, which may be problematic for coastal/subsea disposal. In particular, for deeper water without any islands, shafts over the disposal footprint may be impossible and all access may be by ramps from land. For this reason, access ramps will be longer and take more time to excavate, while ventilation and drainage capacities will also increase. For a coastal site, therefore, tailored concepts for both onshore and offshore variants may be needed and a more detailed assessment methodology developed to assess their relative pros and cons. This is identified as a priority area for future R&D.

4.8.3 Future perspectives

A practical design technology for constructing a repository with the required safety functions has been illustrated and the specifications of the EBS and other major structures have been prepared. Proposed future efforts to increase safety and cost-effectiveness of the repository, based on assured practical, quality-controlled procedures and technology are summarised in Table 4.8-1, organised from consideration of the EBS, surface and underground facilities, and retrievability.

Table 4.8-1 Future major efforts related to engineering technology

Area	Main topics
EBS	• Alternative EBS materials and design options • Improvement of the containment function of the TRU waste EBS • Development and demonstration of technology to evaluate evolution of the EBS • Standardisation of EBS design methods and material property tests • Development and demonstration of EBS fabrication techniques and emplacement technology
Surface and underground facilities	• Development of holistic design technology for the entire repository • Development of technology to ensure safety during construction • Development of repository sealing/closure technology
Retrievability	• Development and demonstration of waste recovery technology • Development of impact assessment technology to evaluate issues arising from maintaining ease of waste recovery

(1) EBS

(i) Alternative EBS materials and design options

In Section 4.4.1, the HLW EBS comprising a steel overpack and a bentonite buffer was shown to meet design requirements for both fresh and saline groundwaters. Here, the carbon steel overpack assumes manufacture by forging, but cast steel could also be considered from the viewpoint of economics. Cost reduction may also be achievable by a thinner steel overpack based on the more realistic assessment of the corrosion allowance, which may also lead to a reduction of the volume of bentonite buffer, since the diameter of the overpack can be decreased. This cost reduction may be more significant in the case of the PEM, since the size of metal shell surrounding the bentonite backfill can be reduced.

It is also recognised that further R&D may allow alternative overpack materials or designs to be considered, for example including protective coatings (e.g. thick copper electroplating [159]), with the aim of assuring the containment function for a wider range of conditions, while also reducing of costs. With regard to the bentonite used for the buffer, work to date has focused on Kunigel V1 Na-bentonite. However, from the viewpoints of economics and procurement diversity, it is necessary to confirm the applicability of other bentonite materials. Thus, various alternative EBS materials and design modifications to allow tailoring to the geological environments of actual sites will be evaluated.

In addition to safety, in the future it will also be important to develop design options taking into consideration the efficiency of operations and the ease of recovery. For example, although the overpack lid has a flat plate structure in the current specification of the overpack, a hemispherical structure [159] [160] can alleviate stress concentration and improve pressure resistance.

From the viewpoint of operational efficiency, the PEM option has clear advantages but, as this method is relatively new, further assessment of its design would be useful to determine how performance can be better quantified and details modified to tailor to specific geological environments. Indeed, from the lessons learned in this chapter there seems to be potential to apply the PEM concept to TRU waste as a new design option.

(ii) Improvement of the TRU waste EBS containment function

In Section 4.4.2, TRU waste EBS specifications were developed, which were shown to meet operational safety requirements under normal conditions and also, for a more robust waste package, ensure containment of RNs for several hundred years after closure. In order to ensure the containment performance of such design options, however, it is necessary to further confirm the robustness of the waste package under abnormal conditions (e.g. by drop tests, fire resistance tests, etc.). In addition, further assessment of issues required for evaluation of long-term behaviour after closure, such as stress corrosion cracking in welds and increases in internal gas pressure, will be carried out with the goal of strengthening arguments for long-term containment by the waste package as a key part of the safety case.

Furthermore, from the viewpoint of further improvement of TRU post-closure performance, ongoing R&D has focused on improved barriers for mobile, highly soluble radionuclides such as I-129 (which contributes greatly to doses), both in terms of better immobilisation within the waste package and higher performance buffers/backfills (e.g. incorporating anion exchangers or getters).

(iii) Development and demonstration of technology to evaluate long-term behaviour of the EBS

Most of the material property tests so far have been conducted for short periods, up to several years; in the future, however, longer-term tests to refine models of behaviour that will reduce uncertainty in temporal extrapolations will be included. For example, since the corrosion rate tends to decrease as the test period becomes longer, corrosion tests lasting more than 10 years in relevant environments could greatly improve understanding and allow more realistic assessment of overpack/waste package lifetimes, serving as a basis for refining their designs. In addition, a further aim is to advance the understanding of interactions within the near field and evolution of the EBS, including impacts of the early THMC transients. Thus, system evolution tests will be carried out, for example on the PEM and the different TRU waste packages, both in the laboratory and in URLs. The acquired data will be used for evaluation of the post-closure performance of the EBS and verification or improvement of the associated models. However, for the complex coupled phenomena occurring in the EBS, it is necessary to monitor behaviour of individual components and the interfaces between them in a comprehensive manner. Thus, to maximise benefits of real-scale tests using simulated waste in underground environments, it is necessary to develop a new generation of high-precision sensors with long-term durability under in situ conditions.

(iv) Standardisation of EBS design methods and material property tests

In order to ensure the compatibility of technology and consistency in the design and construction of the EBS, an aim will be to improve the standardisation of both existing material property test methods for engineered barriers and also new methodology that will be developed in the future. This will lead also to standardisation of design methods (evaluation methods for design requirements, etc.) and the management of data used by these. A useful test case for such standardisation will be the planning, implementation and interpretation of large-scale, in-situ demonstration tests.

(v) Development and demonstration of quality-assured EBS fabrication techniques and emplacement technology

Extensive development of the fundamental technology for overpack and buffer construction has been carried out in Japan. However, in the future, targeted development will be carried out to rationalise and test in full-scale demonstrations the technology for:

- Waste package production and remote inspection.
- Production and construction of the buffer.
- PEM fabrication.
- Production and emplacement of TRU vault infill.
- Waste transport and emplacement, together with other EBS components, using remote control or automated methods.

In terms of the manufacturing technology of overpacks, it is important to promote development of lid bonding technology as well as manufacturing technology for alternative materials. As welding technology, the applicability of TIG, MAG and electron beam welding has been confirmed at full scale for steel overpacks, so it is necessary to now focus on rationalisation, such as shortening the welding time. Nevertheless, developments in such technology will be monitored to check if any new developments would provide benefits for Japanese boundary conditions (e.g. friction stir welding, alternatives to welding). From the viewpoint of preventing stress corrosion cracking, it is important to reduce the residual stress in the weld zone, and hence work on the practical application of techniques such as heat treatment after welding will be carried out. With regard to inspection techniques for welds, the applicable techniques may be constrained by the radiation environment and the requirement that these are suitable for remote controlled operation. In general, these welding and inspection techniques would be common for both HLW overpacks and TRU waste packages. For all developed technologies and associated tests, strict quality control methods will be established that include specifications, inspection standards and definition of responses when specifications are not met.

The PEM construction specification leads to a weight of about 37 Mg (see Section 4.4.3 (1) (ii)) and thus it is necessary to rationalise transport/emplacement techniques in order to assure efficiency while also providing all pre- and post-closure safety functions. In addition, since the PEM handling shell is an additional EBS component, examination of potential barrier roles (e.g. providing containment for a period before it fails, reduction of uncertainty with respect to buffer saturation during a THMC transient) and possibly increased system complexity (shell-backfill and shell-buffer interfaces) is important. Further, as noted in Section 4.4.3 (1) (ii), although PEM emplacement is relatively insensitive to water inflow, it is necessary to demonstrate the practicality of backfilling the gap between the PEM and the disposal tunnel wall surface to required quality specifications under realistic environmental conditions. Development of H12V construction technology is supported by basic research, including a full-scale demonstration in a URL. In the future, in addition to tests of alternative bentonite materials and establishing quality control methods, it will be necessary to develop a practical moisture control technology in order to improve applicability in a wider range of emplacement environments.

Technology for manufacturing TRU waste packages and their installation, together with associated infill, is being further developed with the aim of improving performance in terms of containment after emplacement and ease of retrieval. A full-scale demonstration study will support development and testing of EBS specifications and establishing quality control methods for manufacturing and construction technology.

Waste handling equipment is a focus for advanced technological development, including specific, fail-safe designs for gripping, positioning and placement for the different waste options, both above and below ground. Again here, it is important to carry out demonstration tests using simulated waste in surface and underground research facilities to support development of prototypes and establishing quality control methods. Through these tests, it is aimed to improve practicality and efficiency by the second part of the PI stage. Additional tests will be needed in a site-specific UIF within the DI stage, to confirm that the planned handling and installation methods would be practical. The location of the UIF relative to the emplacement panels also needs to be considered in future design work. In addition, for all equipment related to EBS manufacture and emplacement, it will essential to establish remote operation and/or automation technology to meet radiation protection goals.

(2) Surface and underground facilities

(i) Development of holistic design technology for the entire repository

The underground facilities are very large and complicated by parallel construction and operation, with the requirement to assure independent ventilation and drainage of these two zones, including re-classifying non-controlled and radiation-controlled zones as the project progresses. In addition, due to the long operational time, a programme of inspection, maintenance and, possibly, refurbishment will be needed. Clearly, there is a substantial knowledge base that could be drawn from the design of other nuclear facilities, tunnels or mines, but some issues will be unique to a repository, especially considering the potential for unknown siting environments.

In Sections 4.5.4 and 4.5.5, outline designs for ventilation and drainage systems were presented but, in the future, these will need to be refined based on site-specific assessments of likely groundwater inflow (including abnormal flows as a result of perturbations) and ventilation needs for both construction and operation, with special consideration of responding to fires.

Approaches to meet the design requirements for specific tunnels, shown in Section 4.5.2, and for the layout of the repository, shown in Section 4.5.4, will need to be assessed and, if required, modified based on experience gained from underground demonstration tests. This will be complemented by continuous maintenance and updating the information/knowledge base that is the foundation for judging suitability, developing specifications and setting standards. When the geological environments of real sites are defined in the future, specific risks of potential perturbations impacting operational safety can be identified and, based on analysis of past accident cases and experience in other nuclear facilities, countermeasure can be developed that are reflected in the design of both surface and underground facilities.

(ii) Development of technology to ensure safe repository construction

It is important to develop excavation techniques for disposal tunnels and vaults (plus disposal holes if included) that minimise the perturbation of surrounding rock while ensuring safety and cost-effectiveness. Section 4.5.7 (1) assessed excavation techniques, indicating that those applied in general tunnel construction would be suitable. However, with the goal of improving safety and efficiency, it is intended to study tele-operation and/or automation of excavation technology. Although relevant knowledge is being developed through tests around tunnels in deep URLs, there is a lack of knowledge about the long-term evolution of hydraulic, chemical and mechanical characteristics of the EDZ for different host rocks and hence more extensive study in this area is required.

As shown in the examination of required reserve areas in Section 4.5.4 (5), judgement of whether or not waste should be placed in specific locations depends on possible countermeasures to undesirable conditions, particularly groundwater inflow. Managing groundwater inflow is also very important in order to minimise the perturbation of local hydrogeological conditions and reducing the cost of wastewater treatment. Thus, future work will examine counter measures such as grouting with cementitious material, which is used in general tunnel construction and its application has been confirmed under relevant high groundwater pressure in Japanese URLs [122] [123]. However, in the future, reducing the chemical impact of grout will be examined, either by reducing the amount used to the extent possible or by selecting alternative grouts. In this regard, it is important to recognise that grouting actions need to be considered in the context of networks of tunnels in a disposal panel, where chemical interactions between them can be significant and need to be assessed by a panel-scale hydrogeological model, and hence improvements in assessment methodology are required to guide grout optimisation approaches.

In terms of relevant knowledge capture, advances at the leading edge of tunnelling technology will be followed. For example, in 2015, construction for the Chuo Shinkansen in the Japanese Southern Alps involved one of the world's longest mountain tunnels (about 25 km), with an overburden of up to 1,400 m. The construction technology required and groundwater management countermeasures utilised may well fit repository design requirements and hence developments in this and other similar projects will be kept under review.

(iii) Development of repository sealing/closure technology

With regard to sealing technology, including plugs and backfill to prevent tunnels from acting as hydraulic short-circuits, evaluation is required of their role in the performance of the entire repository for a range of relevant geological environments, which will allow further refinement of the design concepts outlined in Section 4.5.3 and assessment of their practicality. In terms of the performance of the tunnel seals, individual components of the hydraulic plug and backfill, as well as combinations of these, will be assessed in terms of impacts on post-closure repository performance under realistic geological settings. With regard to construction technology, based on the design concepts examined so far and the results of research in other countries, required technology will be developed that is capable of flexibly responding to diverse geological environments and disposal concepts. This technology will be tested in full-scale experiments in surface and URLs in order to develop detailed design specifications, which will also consider countermeasures against possible perturbations and required quality assurance.

(3) Retrievability

(i) Development and demonstration of waste recovery technology

In order to assure practicality of retrieval before final repository closure, it will be necessary to develop and test the required technology. As described in Section 4.7.2 (1) (i), development and testing of such technology for the H12V option is in progress. In the future, it will be necessary to confirm its applicability to the PEM option, noting what components can be taken over from H12V and what modifications/new technology would be needed. In addition, retrieval technology is required for the more complex and less-studied TRU waste case, requiring highly flexible and reliable methods that could ideally be tailored to the different waste groups and package types under consideration. In all cases, practicality needs to be tested in large-scale demonstration experiments that simulate expected conditions for retrieval at different times after emplacement and establish rigorous quality guidelines that can form a basis for later consideration of remote control/automation for actual implementation.

(ii) Development of impact assessment technology to evaluate issues arising from maintaining ease of waste recovery

There can be clear conflicts between the desire to maintain ease of recovery (favouring keeping tunnels open for as long as possible) and assuring operational and post-closure safety, minimising environmental impacts and reducing costs (favouring closing and sealing tunnels as quickly as possible). In Section 4.1.1, the requirement of maintaining ease of retrieval was presented only in rather general terms, along with the need to avoid compromising the performance of engineered barriers. In the future, it will be necessary to extend this assessment to include quantitative analysis of the pros and cons of different options. As these are likely to be site-specific, initial assessment will examine the impacts of maintaining ease of retrieval on safety and environmental impact for different boundary conditions, with a special focus on the hydrogeological characteristics of the host rock.

Supporting Reports (SRs)

SR 4-1 Overview of analysis codes used for design and pre-closure safety assessment
SR 4-2 Set values of the geological environment characteristics used for repository design
SR 4-3 Setting of repository depth
SR 4-4 Overpack design requirements and evaluation items
SR 4-5 Setting minimum overpack thickness
SR 4-6 Setting required corrosion allowance for overpack (initial oxidising environment)
SR 4-7 Setting of required corrosion allowance for overpack (long-term reducing environment)
SR 4-8 Evaluation of stress corrosion cracking and hydrogen embrittlement cracking of overpacks
SR 4-9 Assessment of overpack microbial corrosion
SR 4-10 Setting of the thickness of the overpack for mechanical stability
SR 4-11 Setting the overpack shielding margin
SR 4-12 Assessing the impact of overpack weld defects on structural integrity
SR 4-13 Overpack longevity assessment
SR 4-14 Design of buffer and setting of evaluation items (HLW)
SR 4-15 Technical specifications for HLW buffer
SR 4-16 Technical assessment of compaction properties of HLW buffer
SR 4-17 Evaluation of long-term soundness of HLW buffer
SR 4-18 Calculation of surface and surrounding air dose of overpack and PEM
SR 4-19 PEM handling shell design
SR 4-20 Setting of TRU waste package design requirements and evaluation items
SR 4-21 Setting specifications of TRU waste packages
SR 4-22 Structural integrity evaluation during waste package operations
SR 4-23 Long-term corrosion resistance of TRU waste package B
SR 4-24 Hydrostatic pressure impact assessment for TRU waste package B
SR 4-25 Design of infill between TRU waste packages
SR 4-26 Design of buffer and setting of evaluation items (TRU waste)
SR 4-27 Technical specifications for the TRU waste buffer
SR 4-28 Evaluation of long-term soundness of the TRU waste buffer
SR 4-29 Fabrication and emplacement technology for buffer blocks
SR 4-30 Horizontal PEM: method of emplacement
SR 4-31 EBS construction technology for TRU waste disposal facilities
SR 4-32 Initial concept for design of tunnel liners
SR 4-33 Technical basis for setting disposal tunnel/hole pitch
SR 4-34 Evaluation of HLW tunnel stability
SR 4-35 Design of the disposal cell for TRU waste
SR 4-36 Setting of the TRU waste disposal tunnel cross-section
SR 4-37 Evaluation of TRU waste cavern stability
SR 4-38 Cross section design of other tunnels
SR 4-39 Impact of waste heat on HLW disposal tunnel pitch (H12V)
SR 4-40 Impact of waste heat on HLW disposal tunnel pitch (PEM)
SR 4-41 Impact of waste heat on TRU waste disposal vault pitch
SR 4-42 Setting disposal vault/panel geometry (TRU waste)
SR 4-43 Backfill material specifications
SR 4-44 Setting of the excavation damaged areas for backfill plug design
SR 4-45 Evaluation of long-term soundness of disposal tunnel backfill

SR 4-46 Technical rationale of mechanical plug design
SR 4-47 Technical rationale for hydraulic plug design
SR 4-48 Impact of geological features on layout of the underground facility
SR 4-49 Groundwater flow analysis to support selection of disposal panel locations
SR 4-50 Setting of approach to disposal tunnel (HLW)
SR 4-51 Setting disposal panel dimensions (HLW)
SR 4-52 Setting disposal panel layout (HLW)
SR 4-53 Design of access to TRU waste disposal vaults
SR 4-54 Orientation of disposal panels
SR 4-55 Setting of piping erosion evaluation period
SR 4-56 Evaluation of piping erosion of buffer
SR 4-57 Evaluation of disposal hole utilisation efficiency (H12V)
SR 4-58 Evaluation of disposal tunnel utilisation efficiency (PEM)
SR 4-59 Evaluation of disposal vault utilisation efficiency (TRU)
SR 4-60 Study of work flow and ventilation paths (plutonic rock/HLW)
SR 4-61 Study of work flow and ventilation paths (Neogene sediments/HLW)
SR 4-62 Estimates of excavated spoil volumes (HLW)
SR 4-63 Underground facility ventilation and cooling
SR 4-64 Evaluation of groundwater inflow volume
SR 4-65 Relevant regulations for abnormal conditions assumed during design
SR 4-66 Conceptual designs of underground waste transport vehicles
SR 4-67 Repository excavation technology
SR 4-68 Safety measures during transportation to the repository
SR 4-69 Outline of HLW reception, inspection, and encapsulation facility (H12V)
SR 4-70 Design of connections between the surface facility and access tunnels
SR 4-71 Overview of TRU waste reception, inspection and packaging facilities
SR 4-72 Shielding design for the HLW reception, inspection and encapsulation facilities
SR 4-73 Shielding design for the TRU waste reception, inspection and packaging facilities
SR 4-74 Examination of safety measures for surface facilities
SR 4-75 Engineering feasibility of PEM recovery

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5 OPERATIONAL SAFETY ASSESSMENT

Based on the strategy for operational safety assessment described in Section 2.4.1, this chapter will:

- Develop the strategy and methodology for assessment of the radiological impact to the public in the vicinity during operations, taking into account similarity to other facilities handling HLW and TRU waste and existing safety regulations for nuclear facilities.
- Preliminary assessment of operational safety for current design specifications of the disposal facility.
- Identify key findings and future perspectives.

Section 5.1 describes the strategy and methodology for operational safety assessment. Section 5.2 describes the operational processes, waste characteristics and throughput as background for this assessment. Sections 5.3 and 5.4 describe assessment results of normal and abnormal operational scenarios, respectively. Based on these assessment results, Sections 5.5 and 5.6 describe an approach to post-accident responses, together with a summary and an outline of future work.

5.1 Strategy for operational safety assessment

As described in Section 2.1.2 (2), operational safety assessment covers both radiation protection and conventional hazards. This chapter will focus on potential radiological impacts to the public in the vicinity of the repository, based on the design and operational plan presented in Chapter 4. As also described in chapter 4, the design measures and scenarios described as event-trees are based on the defence-in-depth principle, which also means that the output of the operational safety assessment is a key source for further improving design.

Since safety regulations have not yet been developed for geological disposal facilities, the reference abnormal states assessed in this chapter were selected, and the assessment procedure determined, by consideration of similarities to other facilities handling radioactive waste and associated regulations, together with the safety case methodology and safety assessment guide [1] issued by the IAEA. Here it should be noted that lessons learned from the TEPCO Fukushima Daiichi Nuclear Power Station accident led to development of new safety regulations for nuclear reactors that have already been enforced and which emphasise resilience, even in the event of potential accidents with low probability of occurrence.

The operational safety assessment will be performed for operational scenarios established by reviewing the geological disposal facilities and safety measures described in Chapter 4. Assessment of conventional safety was not included in this Chapter, as it requires detailed designs which will only be developed at later stages of the programme. Furthermore, safety issues related to underground construction and operation could in the future, to a large extent, rely on existing mining and tunnelling practice. Nevertheless, measures contributing to conventional safety, such as maintaining good work conditions, are summarised in Table 2.1-4 and described in more detail in Sections 4.5.5 and 4.5.6.

5.1.1 Procedures for developing operational safety assessment scenarios

Scenarios were developed for both normal and abnormal operations by referring to the

IAEA guide on safety case methodology and safety assessment [1]. The guide states that the safety case must include measures to mitigate any risks to workers and the public in the vicinity of the repository. Such safety measures are described in Section 4.5.6 for underground facilities and Section 4.6.2 (6) for surface facilities. The strategy for developing relevant scenarios is described below.

(1) Procedure for developing normal operation scenarios

These scenarios describe the planned activities in the facilities during normal operation, as outlined in Chapter 4, aiming to assess radiological consequences to the public when the safety functions of radiation shielding and containment during operation (see Tables 4.2-1 and 4.2-2) work normally.

Normal operational scenarios are developed taking into account the following:

- As described in Section 4.6.2 (5), shielding by the walls of radiation-controlled areas should ensure protection of workers, when combined with other radiation control methods that limit and monitor exposure to radiation.
- For HLW, the containment of radionuclides (RNs) is ensured by the glass matrix and the welded stainless steel canister before encapsulation, with the additional overpack and transport cask after encapsulation as described in 4.6.2 (5) (i). Additional containment would be provided by the PEM shell and buffer for the PEM case.
- These constraints are basically similar for TRU waste, as shown in section 4.6.2 (5) (ii).

The following issues are excluded from the normal operation scenarios considered in this report:

- Internal radiation exposure of the public around the facility: RNs are assured to be confined in the specific zones handling radioactive waste, as shown in the design of the waste reception/inspection/encapsulation facilities in Section 4.6.2.
- Radiological effects from underground facilities during normal operation: these are sufficiently shielded by bedrock that no exposure to the public is possible.
- Total doses to radiation workers: as shown in Sections 4.5.6 and 4.6.2, control of access to zones containing radioactive material, remote-handling methodology, shielding and other radiation control is assumed to assure safety.

(2) Procedures for developing abnormal operation scenarios

Abnormal operation scenarios are developed to assess the risk of RN release from the facility due to perturbations of planned activities. To assess how the safety measures described in Sections 4.5.6 and 4.6.2 (6) could be perturbed, the sequential transition from normal operation is captured in an event tree diagram. The event tree in which all safety measures fail is selected as a worst-case abnormal operation scenario.

As show in Figure 4.2-7, an abnormal operation scenario starts from initiating events, such as external hazards (natural events and human-induced events) or internal initiating events (drop, internal fire, explosion, loss of off-site power and other system failures). Scenarios in terms of external hazards involve seismic impacts, tsunami impacts, damage to off-site power, forest fire, electromagnetic impacts, and other impacts on the facilities due to external hazards (see also Table 4.6-1). These impacts may also lead to internal initiating events [2], while the magnitude of impacts may strongly depend on the site environment. In the following section, it is assumed that internal initiating events occur independently of the external hazards, and therefore the scenario will start from the internal initiating events in a site-generic and conservative manner. This approach also covers scenarios due to internal initiating events which are not caused by external hazards

The following points were considered when creating the event trees used to develop the abnormal operation scenarios:

- The event trees illustrate the process where assumed initiating events lead to abnormal states (e.g. drop or fire) that result in mechanical or thermal impacts on waste.
- Since the aim is to assess the possibility of RN release from the facility as a result of accidents, the event tree does not include measures to mitigate the effects and accident management after loss of containment.
- Safety culture and education of workers are important safety measures. However, the event tree does not include such measures explicitly, although their failure may be a root cause of perturbations leading to abnormal operation, while their contribution to detection of failures leads to identification of disturbances and associated counter-measures to reduce impacts and allow recovery of normal operations.
- Although multiple perturbations may occur simultaneously (common mode failure), for assessment of the direct effectiveness of counter-measures discussed in Sections 4.5.6 and 4.6.2 (6), this report does not consider these, but they are highlighted in Section 5.6.2 (1) as a future priority.

The developed abnormal operation scenarios are classified into five groups: drops, fires, explosions, loss of external power, and other equipment failure. As discussed in Section 5.5, this list may not be complete. For example, scenarios resulting from other external events or impacts of irregular waste packages (failure of production quality control) may be considered in the future.

5.1.2 Procedures for assessment

(1) Procedures for normal operation scenario assessment

As described in Section 4.6.2, this section assesses the radiation exposure to the general public from the reception/inspection/encapsulation facility for HLW and TRU waste. Once a repository site is selected, the site boundary will be set based on consideration of local geological, geographical and environmental conditions. Thus, assessment in this report quantifies the annual effective dose, taking the distance from the facility to the boundary as a variable.

To assess the radiation shielding function, direct irradiation and skyshine from the HLW/TRU waste handling facility shown in Section 4.6.2 is quantified, using the 50 μSv/y nuclear facility regulatory dose limit to the general public and determining the distance at which this limit is reached.

(2) Procedures for abnormal operation scenario assessment

Since the RN release from the facility is limited to cases where HLW and its canister/overpack/transport cask, as appropriate, are significantly damaged (in the case of TRU waste, the waste matrix, primary container, waste package and transport cask), an evaluation of the robustness of these is included in the assessment. If damage did occur, both the characteristics and concentrations of RNs released could be used to estimate the radiological consequences. However, such assessment requires topographic, climatic and local lifestyle information, which can be determined only on a site-specific basis. For this reason, this report assesses only the risks of damage to waste form that could lead to RN releases.

A conservative approach is taken in which, before analysis, a key indicator of impact (explained further below) is evaluated for each scenario, and then the worst case selected for analysis.

5.2 Premises for the assessment

As premises required for this assessment, this Section describes:

- The operational processes.
- The waste specifications and throughput.
- Specifications of the repository engineered barriers, surface facilities and repository.

5.2.1 Operational processes assumed in assessment

As shown in Section 4.2.4 (1) (i), during normal operation, wastes are transported to the surface facility in transport casks and received at the reception/inspection/encapsulation facility. Before encapsulation of HLW into an overpack, HLW canisters are temporarily stored before inspection to confirm compliance with waste acceptance criteria. Such storage is in a radiation shielded cell, with negative air pressure to prevent RN release in case of any surface contamination being present. After inspection, the HLW is moved to the encapsulation cell and sealed into an overpack by remotely operated equipment. The waste handling equipment for these procedures, such as overhead cranes or lifts, is designed to prevent waste drops as outlined in Section 4.6.2 (6).

For the H12V case, the overpack is, in the design presented in Chapter 4, placed into a transport cask and moved underground via an access ramp (in the future other means of access may be selected, e.g. shafts). The overpack is transferred to the emplacement machine at the bottom of the access ramp and then moved to, and emplaced in, a disposal tunnel. These procedures are also carried out by remote-control, with strict radiation protection. When tunnels are filled with waste, they are then backfilled and sealed. In the assessment, reference is made to relevant studies performed for similar operations in other nuclear facilities, for example drop tests of HLW canisters have been already documented elsewhere [3] [4]. This report focuses on operational processes specific to geological disposal.

For the PEM case, the overpack is placed inside the PEM on the surface and then transported down into the repository. The detailed technical design for this is not yet decided.

For the TRU waste case, waste package B is placed into a transport container and then transported into the repository. The waste package is then transferred by overhead crane at the entrance to the disposal vault and emplaced at the designated location within the disposal cell. Once a disposal cell is full, gaps are filled with mortar and, after all cells in a disposal vault are full, itis backfilled and sealed. In the case of waste package A, procedures are the same as for waste package B with the exception of emplacement, which is carried out using a forklift.

5.2.2 Waste inventory and planned throughput

(1) HLW repository

Fundamental features of HLW and its overpack were presented in Sections 2.1 and 4.4.1 (2), respectively. Interim storage of HLW before disposal may last for between 30 to 50 years but, when conducting shielding and thermal analyses, 30 years storage is conservatively assumed.

1,000 canisters of HLW are planned to be disposed of annually (see section 2.1.1 (4)). As described in Section 4.6.2 (2), marine transport was assumed to occur twice a year, with 28 units of HLW contained in each transport cask and at least 18 casks in each shipment, so the waste reception/inspection/encapsulation facility is designed with a store capacity for 20 casks.

In the case of H12V emplacement, overpacks are loaded into transport casks with a radiation shielding and physical protection functions, and then moved underground via the access ramp, two at a time, by the transport vehicle (see Supporting Report 4-66). At the bottom of the ramp, overpacks are transferred to emplacement machines, one by one (see Section 4.4.3 (1) (i)). The emplacement machine transports the overpack to a disposal tunnel and then lowers it into a disposal hole (see Section 4.4.3 (1) (i)). These procedures are also carried out by remote-control with strict radiation protection. When tunnels are filled with waste, they are then backfilled and sealed.

The PEM concept process is the same as for H12V until the overpack is sealed. Thereafter the overpack is put into the PEM handling shell, together with buffer material. The PEM provides radiation shielding and also physical protection of the overpack and hence no transport shielding is required.

(2) TRU waste repository

The fundamental features of TRU waste are described in Sections 2.1(2) and 4.4.2 (2), whilst the amount of waste handled annually is specified in Section 4.6.2 (2).

TRU waste transport casks are assumed to be delivered to the repository by ship [5], six times a year, for 25 years of operation. For the case of drums, depending on size, two or four are grouted into waste package containers in the surface facilities, placed into a single transport cask, and then moved underground to the disposal vault. The Gr.4L box containers are moved directly underground. Waste package unloading and emplacement in a concrete vault utilises a forklift for waste package A or an overhead crane for waste package B (see Supporting Report 4-66). After a specified number of waste packages are emplaced in a disposal cell, gaps between waste packages are filled with mortar. In the case of forklift emplacement, the technology for this backfilling has not yet been decided. After completion of emplacement of all waste packages in the vault, the top backfilling material and plugs are installed.

The radiological and thermal properties of TRU waste, which will be considered for shielding analysis, are described in Supporting Report 2-3. For the fire impact analysis, among the categories of TRU waste, bituminised waste requires particularly careful handling, because runaway thermal reactions can lead to spontaneous ignition at temperatures higher than ≈ 200 °C [6]. For the physical impact analysis of the drop scenario, waste groups of 1, 3, 4L and 4H, which utilise drums, are assessed.

5.3 Assessment of normal operational scenarios

Radiological exposure of the public from the repository is assessed based on the strategy described in Section 5.1.

For the HLW repository, the inventory of radioactive waste at the surface is highest at the reception/inspection/encapsulation facility (see Figure 4.6-2) when 20 transport casks are present in the buffer store and 28 HLW canisters from a single cask are stored prior to inspection. For this case, the annual effective dose is calculated as a function of distance to the site boundary. The radiation exposure from other areas is negligible in comparison, as only a few HLW canisters are present and they are located in the basement of the facility, with radiation shielding provided by both concrete floors and surrounding soil, as shown in Figure 4.6-2.

In assessment of the temporary storage area for transport casks, since the specification of these casks [7] is in accordance with the transport regulations [8] shown in Section 4.6.1, it can be assumed that the dose rate is less than 2 mSv/h and 0.1 mSv/h at the surface of the cask and at a distance of 1 m from it, respectively.

Exposure by direct and skyshine radiation is assessed to ensure it falls below the annual effective public dose target of 50 μSv/y, which can be demonstrated if a distance of 200 m or more from the facility to the site boundary is set. The details of the very conservative shielding analysis are given in Supporting Report 5-1. For both the H12V and PEM options, the process from reception to encapsulation of HLW in an overpack is the same and therefore there is no difference in the results of this assessment.

For TRU waste, the assessment was performed in the same manner as for HLW, the radiation exposure considering both the buffer stores for transport casks and waste packages waiting for inspection. It is concluded that, if the distance from the facility to the site boundary is more than 100 m, the annual effective dose falls below the target of 50 μSv/y. The details of the analysis are given in Supporting Report 5-2. The processes until waste packaging are the same for both waste packages A and B, as shown in Section 4.4.2 (2), and hence there is no difference in the assessment results.

From the above, when the HLW and TRU waste facilities are located at the same site, the effects from each waste are summed in the assessment. Since the radiation effect from HLW is significantly larger than that of TRU waste, by maintaining a distance of 200 m or more from facilities to the site boundary, the dose target of 50 μSv/y can be met. If the distance to the site boundary is less than this at a specific site, the thickness of the shielding walls of the facility could be increased to reduce the dose rate. It should also be noted that the dose calculations are very conservative and do not take account of shielding by other surrounding buildings. In addition, greater shielding can be obtained, if required, by locating buffer stores underground.

5.4 Assessment of abnormal operation scenarios

The radiological consequences of abnormal operation scenarios were assessed taking account of the safety measures developed (see Sections 4.5.6 and 4.6.2 (6)). All individual procedures in which waste is handled are subject to a formal event tree analysis, which assesses how the normal defence in depth to prevent occurrence of abnormal states could possibly fail. The abnormal states considered can be grouped in terms of the operation involved, as many of them have similarities that allow them to be treated together when assessing their impacts on HLW or TRU waste.

5.4.1 Development of abnormal operation scenarios

The abnormal operations described in Sections 4.5.6 and 4.6.2 (6) result from perturbations including drops, fires, explosions, loss of external power and other equipment failures. Event-trees were developed for situations when safety measures fail or the perturbations exceed those assumed during design. Event trees that resulted in potential loss of the containment function were selected to develop abnormal operation scenarios.

(1) Drops

(i) HLW

Assessment of drops with the PEM during operation has not yet been performed, although consequences will be similar to or less than those for H12V. Operations that could lead to possible drops of the HLW transport cask, canister or overpack for the H12V option include:

- The process of lifting and moving transport casks in the buffer store (see Figure 4.6-2).
- The process when HLW canisters are lifted out of the transport cask by the overhead crane and moved to the inspection and temporary storage area and then into the overpack (see Figure 4.6-2).
- After encapsulation, the process when an overpack is moved into a buffer store and then loaded onto the transport vehicle by overhead crane (see Figure 4.6-2).
- The process when the overpack is transferred from the transport vehicle to the emplacement machine by overhead crane at the bottom of the access ramp (see Section 4.5.4 (4) (iii)).
- The process when the overpack is lowered into disposal holes (see Figure 4.4-26).

Figure 5.4-1 shows typical event trees for the drop of an overpack during handling by an overhead crane, including the safety measures shown in Table 4.5-34. The other cases of drop of a transport cask or a HLW canister (or indeed a TRU waste package B) can be described by similar event-trees.

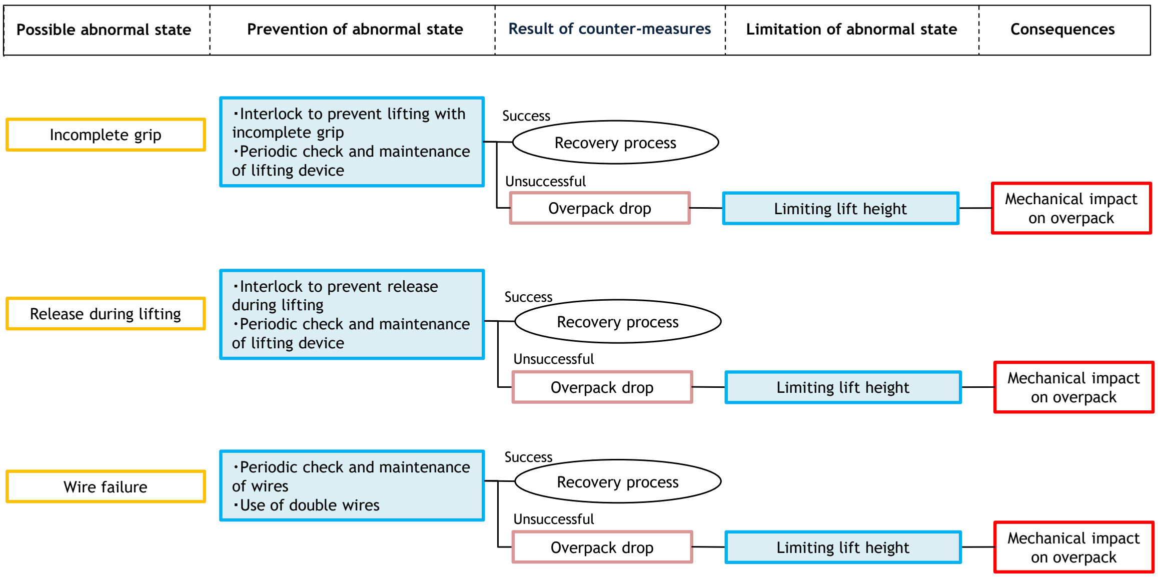

Figure 5.4-1 Event tree for drop of a HLW overpack

Drops could occur if the overpack is lifted with incomplete gripping, if gripping is wrongly released during lifting or transport, or if the lifting wire is damaged. It should be noted that this focuses only on the gripping mechanism and ignores other possibilities, such as failure of the winch or derailing of the crane. Such aspects will be considered in future assessments.

In order to prevent such perturbations, lifting wires are duplicated and interlocks are installed in the gripping device. However, if these safety measures fail, impact forces act on the overpack and contained waste, although a fundamental constraint is set by physical limitation of the handling height, which prevents excessive drops.

In Section 5.4.2 (1) (i), the effects of drop scenarios are assessed.

(ii) TRU waste

As described in Section 4.4.3 (2) and Figure 4.4-27, waste package A is handled by forklift and waste package B by an overhead crane. As such, the following operations may be causes of a waste drop:

- The process of lifting and moving transport casks in the buffer store (see Figure 4.6-5).
- The process when TRU primary containers are lifted out of the transport cask by overhead crane and moved to the inspection and temporary storage area (see Figure 4.6-5).
- The process when TRU primary waste containers are lifted into the waste package by overhead crane (see Figure 4.6-5).
- After production, the process where waste packages are moved to a buffer store and then to the transport vehicle (crane or forklift, only crane option shown in Figure 4.6-5).
- The process that stacks and emplaces waste packages in the concrete cell of the disposal tunnel (refer to Section 4.4.3 (2), Figure 4.4-27).

The event trees for drops are effectively the same as for HLW (e.g. Figure 5.4-1), with safety measures (e.g. limitation of the handling height) as shown in Table 4.5-34. As described in Section 4.4.2 (2) (ii), emplacement by overhead crane uses a twist lock gripping system (see also Figure 4.4-27) and, in case of failure, a drop may occur.

Waste package A is assumed to be moved by a waste package conveyor and lifted by forklift only during transporter loading and unloading/waste emplacement (as shown in the TRU-2 report). Since the drop height is greatest when waste packages are stacked in the disposal vault (See Figure 4.4-29), a waste package drop scenario is developed for this process as described in Section 4.4.2 (2) (ii), with the specified number of layers given in Table 4.5-5.

The forklift incorporates an interlock system which prevents lifting when fork insertion into the lifting pockets is incomplete It also prevents withdrawal of the forks unless emplacement is complete. If a malfunction of the interlock system occurs, e.g. in the case where the forklift backs away before emplacement is complete, a waste package could drop to the floor of concrete vault.

Finally, it should be mentioned that there is also a potential risk of waste stacks toppling; however, this risk has not yet been analysed.

(2) Fires

(i) HLW

The causes of, and counter-measures against, fires in facilities are described in Sections 4.5.6 (2) and 4.6.2 (6) (ii). In the following, only fires in underground facilities are discussed, since there is already substantial experience in assessment of fire impacts in surface facilities. Evaluation of the risks of, and countermeasures against, fires in surface facilities will be included in later stages of the programme. Wherever possible, all construction in the facilities utilises non-flammable or flame-retarding materials. Even if flammable materials are present, limitation of ignition sources would prevent occurrence of fires (and explosions). In addition, fire, gas and smoke detectors, together with alarms and fire extinguishing equipment, will be installed in all sensitive areas.

The following equipment and devices described in Chapter 4 for the H12V option, however, may include combustible materials:

- On the access ramp; transport vehicle, diesel fuel and wheels with rubber tyres.
- At the bottom of the access ramp; hydraulic and lubricating oils used by the overhead crane that transfers overpacks from the transport vehicle to the emplacement machine.
- Diesel fuel and rubber tyres of the emplacement machine that transports overpacks to disposal tunnels and emplaces them into disposal holes.

The ramp transport vehicle is likely to have the largest quantity of combustibles, as indicated in Figure 4.5-36, hence fire scenarios focus on it. It is also recognised that diesel may not be used in the future, as electric vehicles are then more likely, and fire hazards for electrical vehicles will also need to be assessed. Event trees for fire scenarios are shown in Figure 5.4-2, based on the design of the transport vehicle (Supporting Report 4-66).

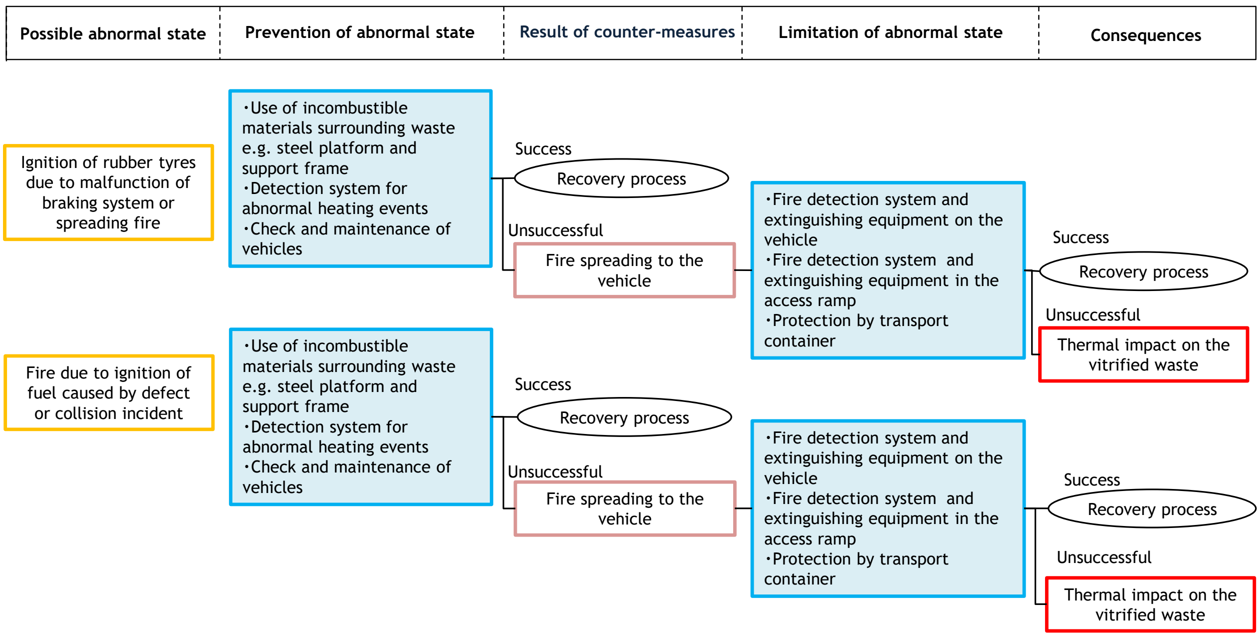

Figure 5.4-2 Event trees for HLW transport vehicle fire in an access ramp

Since diesel oil and rubber tyres have the highest potential heat production, these are set as fire sources (see Figure 4.5-36).

The tyre fire scenario is described as:

- During transportation on the access ramp, one of the transport vehicle rear wheels is abnormally heated due to a braking system malfunction, leading to ignition of a tyre. Alternatively, a small fire, e.g. due to leakage of gear oil, spreads to ignite a tyre.
- The operator would notice this fire, but attempted fire extinguishing operations fail, allowing the fire to spread to adjacent tyres.
- Air heated by the fire and thermal conduction through the vehicle deck would warm the transport cask and, by conduction, also its contents.
- Even after the fire burns out, the deck temperature remains high and will continue to heat the cask and its contents by thermal conduction.
- In the case of diesel oil pool fires, the scenario assumes fuel would leak to the tunnel floor and be ignited due to an abnormal state involving the transport vehicle.

In the PEM case, the thermal impact to HLW will be lower than H12V, since the overpack containing HLW will be surrounded by thick bentonite buffer which restricts heat conduction. Thus, in Section 5.4.2 (2) (i), the thermal effects of fires on HLW are assessed for H12V only.

(ii) TRU waste

Fire scenarios for TRU waste are effectively the same as for HLW; so Figure 5.4-2 can be applied.

As shown in Table 2.1-2, most of the TRU wastes comprise inorganic material (mortar and metal) and non-combustible wastes, therefore spontaneous ignition (or explosion) is unlikely and fire impact assessment is similar as to that for the HLW case. An exception is the Gr.3 waste, which is assumed to be stable at ambient temperatures in the underground facility (about 30 to 45 °C), but the bitumen and nitrate mixture has a risk of spontaneous ignition if the waste is exposed to higher temperatures [6]. Fire scenarios thus focus on this waste, as consequences are likely to be more severe than for other TRU waste groups.

(3) Explosions

As discussed in Section 4.5.6 (3), the SDMs used in this in this study do not indicate risks from potentially explosive gases and their generation from the waste or other repository components is assumed to be unlikely. Therefore, explosion scenarios are not considered, but the methodology to assess them is under development and is introduced in Section 5.4.2 (3), assuming methane gas occurrence, and will be addressed further in future work.

(4) Loss of off-site power

In this scenario, shutdown of surface and underground facilities due to loss of off-site power is described. In developing this scenario, it is recognised that just loss of off-site power would have little immediate impact on operations, since all systems could be brought to a safe shut-down condition using uninterruptable power supplies, auxiliary generators, batteries, etc. However, as a limiting case and illustrating consequences of a situation that could lead to common mode failure of many safety functions, the consequences of a sudden total blackout, e.g. caused by a massive natural or anthropogenic electro-magnetic pulse (EMP), is worth assessing in the future.

As described in Section 4.5.6 (4) and Section 4.6.2 (6) (iii), sudden loss of power may cause a drop of a HLW canister or overpack being handled by an overhead crane. However, this is effectively the same as for the drop scenarios described in Section 5.4.1 (1).

Loss of power may also cause shutdown of drainage systems in underground facilities. However, for HLW and type B TRU packages, the drainage water would not be contaminated unless failure of radioactive waste containment occurs. For these waste types, the shutdown of the drainage system is unlikely to cause direct RN release during loss of off-site power. However, it should be noted here that longer term impacts of loss of drainage have not yet been assessed, but are recognised as a future priority.

In the reception/inspection/encapsulation facility, negative pressure is established for areas where the possibility of contamination exists, however high-efficiency particulate air (HEPA) filters at air outlets should prevent RN releases even if negative pressure cannot be maintained (see section 4.6.2(6)(iii)). Similarly, in any event where a release of RNs from underground facilities is detected, switching to an emergency ventilation system equipped with HEPA filters prevents RN release from the facilities, if backup power is available (See Section 4.5.6 (6)). However, in the case of total power loss, including both off-site and all backups, shutdown of all ventilation and loss of part of the containment function will result. As long as waste forms are not damaged, RNs will not be released. Therefore, the assessment of the radiological consequences of ventilation shutdown scenarios is included only when the possibility of damage to waste forms results from assessment of other scenarios.

In addition, in the event of ventilation system shutdown, the temperature of HLW in the buffer stores rise and hence this scenario is analysed. Although ventilation systems are not primarily used to cool down HLW, these are assessed as an effect of loss of power.

Finally, it is noted that, apart from the systems assessed above, total loss of power could also include loss of control functions, monitoring systems, lighting and communications. Such impacts will be covered in future studies.

(5) Other system failures

External perturbations, system damage, malfunctions and human errors can result in drops, fires, explosions and power loss, as described above. Many other possible events could impact RN containment and, as an example, an abnormal state involving the ramp transporter vehicle is considered, as shown in the event tree in Figure 5.4-3.

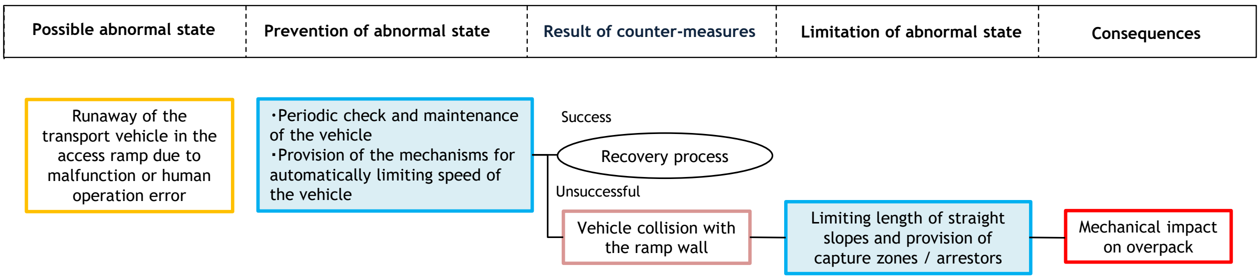

Figure 5.4-3 Event tree for transport vehicle runaway on an access ramp (HLW)

As described in Table 4.5-38, regular maintenance and interlocks with multiple brakes to provide speed limitation are design counter-measures against vehicle malfunctions. Failures of these measures could lead to vehicle runaway and then collision with the tunnel wall. In order to reduce the collision impact, the length of straight slopes could be limited and runaway capture zones/arrestors of the type used on steep ramps included in the design.

This abnormal operation scenario for HLW would be directly applicable also to TRU waste, with "overpack" in Figure 5.4-3 replaced by "TRU waste packages".

5.4.2 Consequence analysis for abnormal operation scenarios

For the abnormal operation scenarios described in Section 5.4.1, consequence analyses are conducted to determine if there is any risk of loss of containment function due to resulting damage. Detailed designs of equipment in the facilities have not been developed at the current generic stage of the programme, and hence failures are assumed without considering potential resilience designed to limit either probability of occurrence or resultant impacts of abnormal operations.

(1) Drops

(i) HLW

Transport casks are designed to resist a drop from a height of 9 m based on transport regulations, so the lifting height limit alone assures that no loss of containment would result from a drop [7] [8].

For assessment of drops of a HLW canister, an analysis of past drop tests indicated that no penetrating cracks occur when the lifting height was less than 9 m, though the canister might be deformed [3] [4]. Thus, prevention of loss of the containment function is achieved by limiting the lifting height to significantly less than this value.

For overpack assessment, a drop from the greatest height possible is assessed – i.e. in the reception/inspection/encapsulation facility, with a limit of 9 m (see 4.6.2 (6) (i)) by taking a conservative approach as described in Section 5.1.2 (2). In underground facilities, as shown in Section 4.5.4 (4) (iii), the lifting height of the overhead crane for transferring overpacks from the on-site transport vehicle to the emplacement machine is 3 times the height of the overpack (1.9 m) and hence significantly less than 9 m. Similarly, the maximum overpack drop from the emplacement machine into the disposal hole is about 4.2 m (floor surface of the disposal tunnel to the bottom of the disposal hole - see Figure 4.5-2), although the presence of buffer in the hole would reduce the drop height further.

For the maximum drop height of 9 m, the free fall velocity of the overpack at collision with the floor surface is calculated, and then elasto-plastic analysis used to assess impact with the concrete floor slab to determine the possibility of generating through-cracks.

The drop onto a concrete floor slab was assumed to occur at an angle, so that the impact occurs on a more vulnerable edge. If the equivalent plastic strain exceeds the breaking strain 0.23 of the carbon steel (SF 340A) used [9] (see Section 4.4.1 (2) (ii)) and connects from the outside to inside of the overpack, penetrating cracks could occur. Figure 5.4-4 illustrates the analytical results, showing that the area exceeding the breaking strain limit was found only near the collision point and thus no crack penetration would occur. The details of this analysis are provided in Supporting Report 5-3.

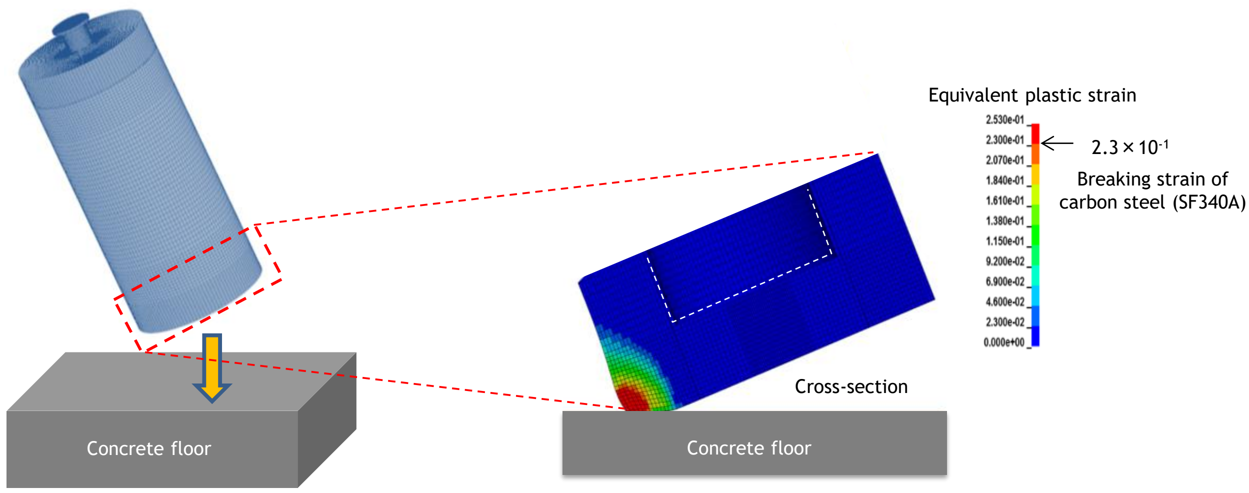

Figure 5.4-4 Physical analysis of overpack drop

In the case of the PEM option, after emplacement in the handling shell, drop impacts onto the overpack are physically reduced by the PEM handling shell and the buffer material, so damage would be even smaller.

(ii) TRU waste repository

As for HLW, drops of transport casks are not a concern. To prevent loss of the containment function, the lifting height is physically restricted in designs of equipment and systems as in the HLW case [7] [8]. As described in Section 4.6.2 (6) (i), the lifting height of drums (Grs.1, 3, 4L, part of 4H) will be designed to be less than 6 m [10], while Gr.2 and Gr.4L (box container) lifts are less than 9 m.

The mechanical durability of wastes solidified into other containers has not been assessed, because these waste containers have not yet been fully specified. After such specification, the same assessment of drop consequences as for the other waste-forms will be made, allowing lifting height limits to be set.

For type B waste packages lifted into disposal vaults by overhead crane (See Figure 4.4-27 and Section 4.6.2 (6) (i)), the maximum drop height was assumed to be the maximum lifting height of 8 m, (the lifting height during stacking is less than 8 m). As described in Section 4.6.2 (6) (i), based on past drop tests, no failure of canisters of Gr.2 waste and box containers of Gr.4 waste were observed up to a height of 9 m while, in the case of drums, lid failure was reported for drops from 6 m or more. As an example, an elasto-plastic analysis simulating a drop of waste package B containing drums was conducted, with the possibility of through-cracks assessed as for the HLW overpack, using the breaking strain 0.24 of the carbon steel (SM400A) used [11] (see Section 4.4.2 (2) (ii)).

The worst-case drop of the waste package was considered to be when a corner of the upper surface, which has the twist-locks, lands on the concrete floor, so this was the case modelled. Figure 5.4-5 illustrates the analytical results, showing that areas where the equivalent plastic strain exceeds the breaking strain were found, however fracturing is considered unlikely because the area where the failure criterion are exceeded was very limited.

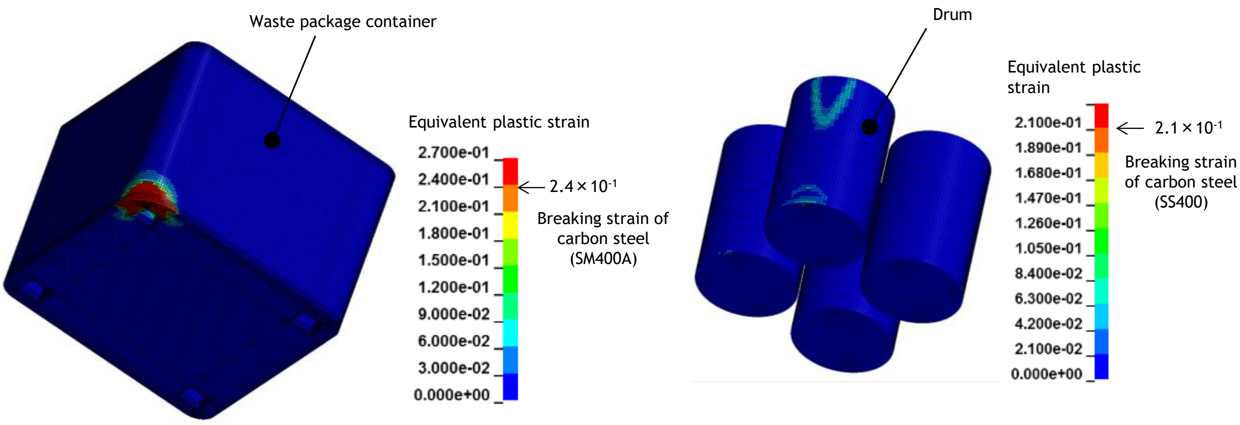

Figure 5.4-5 Results of physical impact analysis for a type B waste package containing 4 drums

In addition, a maximum equivalent strain of 0.08 of the contained drums was calculated, which is far below the relevant breaking strain (0.21) for SS400 type steel [11] and occurs only in the vicinity of the collision point. Thus, it is clear that there is no risk of RN release. The details of analytical methods and associated calculations for type B waste packages are given in Supporting Report 5-4.

Equivalent scenarios for waste package A assume that the drop occurs during emplacement in the disposal vault by forklift. As shown in Table 4.5-5, the maximum number of waste packages containing drums in a stack is six, for both Gr.3 and 4L vaults. If a waste package drops due to malfunction during the emplacement of the top layer, the drop height is equivalent to the height of the upper surface of the 5th layer (5.75 m). According to drum drop tests [10], the drum could be deformed but the contents will not be released when dropped from a height of < 6 m. In addition, since the drum is solidified with mortar within the waste package, the impact force on it is significantly smaller than when dropped directly. It is thus considered that there is a low probability of package failure, which will be confirmed in future studies.

(2) Assessment of fire scenarios

Fire scenarios considered in Section 5.4.1 (2) focus on the ramp transport vehicle, as discussed in Section 4.5.6 (2), with determination of the resultant temperature increase of the overpack (or TRU waste package). This vehicle has a rack installed on a flatbed deck to hold either two overpack transport casks (for H12V, see Section 4.5.6 (2)) or a single cask for a TRU waste package (see Supporting Report 4-66). The transport casks have a radiation shielding function, but also protect the contained overpack/waste package from physical impacts and fire in case of abnormal states. Transport casks are installed near the centre of the deck, located as far as possible from the fuel tank (see Supporting Report 4-66).

From the design of the transporter vehicle, diesel oil and rubber tyres were determined to be the major combustibles present. Fire duration is calculated for each fire source and compared, with the scenario that has the longer duration chosen for assessment.

(i) HLW

(a) Duration of tyre fires

According to a report of causes of fire in road vehicles [12], a common case involves abnormal wheel heating due to locking of the braking system until ignition of the tyre. The associated uncertainties in this analysis have not been assessed at this point, since it was considered sufficient to look at just one representative scenario to illustrate the assessment process. At later stages, more thorough assessment may be carried out if design changes are not made to eliminate this issue (e.g. change to electric-powered rail transport).

The calculation assumes that, in the event of a fire, ventilation would be stopped to limit air flow, but did not consider fire doors to prevent exhaust of combustion gases through the access ramp, see Support Report 5-6 for details. The duration of fire was calculated assuming that fire from one tyre spreads to those nearby as follows;

- The right tyre of the third axle (denoted as tyre 3) closest to the two transport casks (shown in Figure 4.5-36) ignites.
- As this tyre burns, the right tyre of adjacent second and fourth axles (denoted as tyre 2, tyre 4) are heated and ignite.
- As the right tyre of the fourth axle burns, the right tyre of the adjacent fifth axle (denoted as tyre 5) is heated and ignites.

In order to calculate the fire duration, the combustion analysis used a numerical model of the vehicle, as shown in Figure 4.5-36. Figure 5.4-6 (left) plots the heat generation rate as a function of elapsed time since ignition.

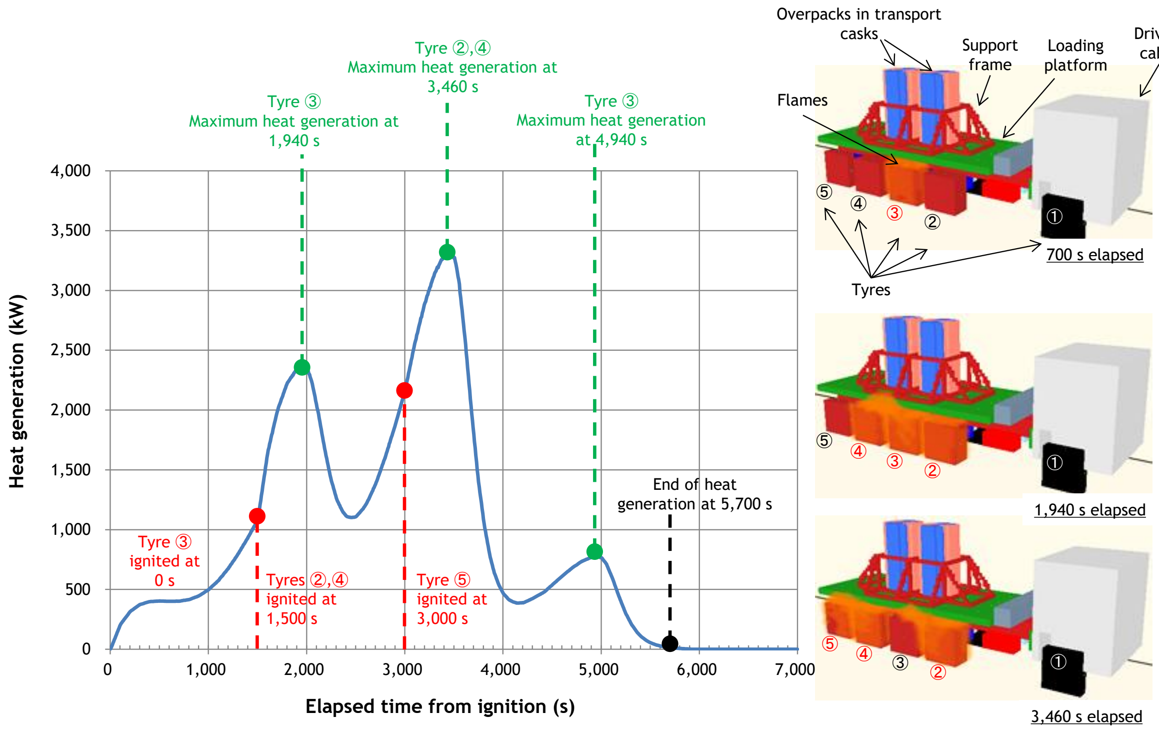

Figure 5.4-6 Combustion analysis for tyre fire of a ramp transport vehicle (HLW)

The ignition condition for rubber tyres was a surface temperature over 400 °C or a heat flux of over 16.5 kW/m^2 [13].

Initially, only tyre 3 on the right side of the vehicle starts burning and then neighbouring tyres 2 and 4 reach the ignition condition and catch fire after1,500 seconds. Finally, tyre 5 catches fire after 3,000 seconds. In this simulation, tyre 1 on the right side of the vehicle and the tyres on the left side did not reach the ignition condition.

The heat generation rate reached a maximum value of 3,300 kW after 3,460 seconds, mainly due to tyres 2 and 4, and decreased to zero at 5,700 seconds when the fire burned out. The fire duration was thus ca. 90 minutes. Figure 5.4-6 (right) shows the distribution of heat around the burning tyres from the numerical model. The flames, represented as orange, are shown to reach upper parts of the flatbed deck, but not the transport casks or the fuel tank. The details of this combustion analysis are provided in Supporting Report 5-6.

The fire model is accepted to be very simple and will be developed further in the future, e.g. to assess the impacts of tyre burst during fire and potential for vehicle to tip, causing flames to reach tyres on the other side.

(b) Duration of fuel fires

The analysis assumes that diesel fuel leaks from a fuel tank to the floor of the tunnel, e.g. due to collision with the tunnel wall or failure of the fuel tank, with fire duration calculated assuming a pool fire. The size of the flame was calculated based on the method described by the Architectural Institute of Japan [14]. The area of the pool of leaked fuel (200 litre), see Supporting Report 4-66) was assumed to be 50 m^2, giving a theoretical flame height of ≈ 11 m, so the flame will reach the 7 m high tunnel roof (see Table 4.5-6). Fire duration was calculated to be 60 seconds, based on the burning rate of diesel fuel and the depth of the pool. Details of the calculation of the fire duration are described in Support Report 5-5. Again, potential uncertainties in these results have not been assessed at this point, since the focus was only on illustrating development and assessment of a representative scenario. Nevertheless, the analysis suggests that a tyre fire would be the limiting event.

(c) Fire impact analysis for HLW

Since the fire duration was longer in the tyre fire case, this was assessed to evaluate consequences. Carbon steel, used for the overpack and waste package, undergoes phase transformation above 727 °C [15], while HLW borosilicate glass may devitrify at temperatures above 610 °C [16] [17]. If these temperatures are exceeded, the integrity of the overpack may be compromised. These temperatures are therefore used as references to assess the potential impact of heating on containment functions.

Figure 5.4-7 shows the distribution of temperature on the surface of the vehicle deck and transport casks, as determined by thermal conduction analysis using the amount of heat input to the lower surface of the deck from the tyre fire combustion analysis.

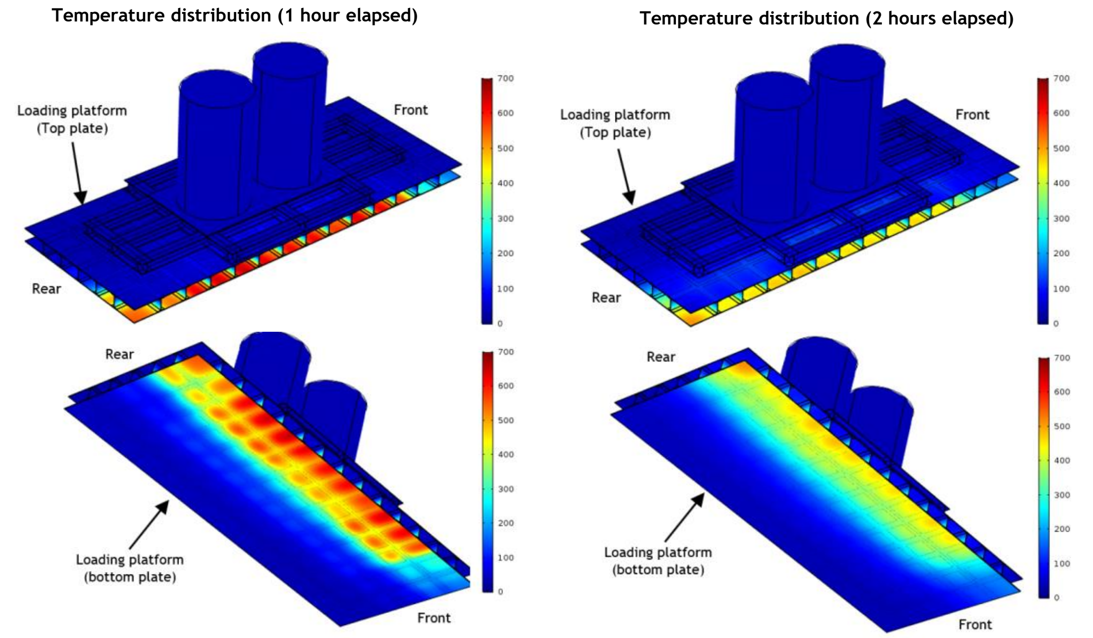

Figure 5.4-7 Temperature distribution of the vehicle deck during the tyre fire (HLW) Since tyres burn only on the right side, major temperature rise is limited to the area above them. The colour legend represents temperature in °C

The temperature of the bottom plate of the deck on the right side of the vehicle where the tyre burns is the highest and rises to 649 °C, however the temperature of the top plate of the deck only rises to 99 °C because of limited heat conduction due to the hollow structure of the deck. In addition, the amount of heat input to the casks was about 0.4 kW at maximum, significantly smaller than the heat generation rate from the fire presented in Figure 5.4-6. This is because flames from the tyres are blocked and dispersed by the deck (see Supporting Report 5-6), as shown in Figure 5.4-6 (right).

Figure 5.4-8 plots the maximum temperatures of the transport cask, overpack and HLW as a function of time. These temperatures were determined by the following procedure:

- Steady-state thermal analysis was conducted to determine the temperature distribution within the HLW overpack.
- The heated overpack sits within a transport cask on the deck of the ramp transport vehicle and transient thermal analysis was conducted assuming that it took 5 hours from loading to moving to a depth of 500 m, where fire is assumed to occur.
- The heat fluxes from the deck of the vehicle and heated air around the transport cask, determined by the combustion analysis illustrated in Figure 5.4-6, were applied as heat input.
- Since heat is transferred from the vehicle deck even after the fire has burned out, thermal analysis was continued for 12 hours from fire initiation.

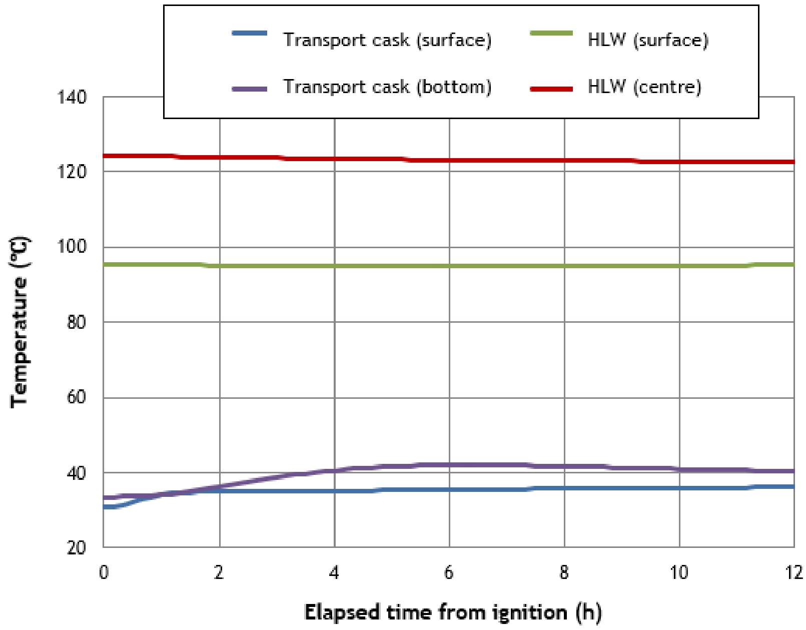

Figure 5.4-8 Temperatures at various positions as a function of fire duration (30 years interim storage of HLW)

The initial temperatures of the centre and surface of the HLW and the surface and bottom of the transport cask at the time of fire were 124 °C, 95 °C, 31 °C and 34 °C, respectively. Figure 5.4-8 shows that the temperatures of the centre and surface of the HLW were almost constant during and after the fire. The temperatures at the surface and bottom of the transport cask increased to 37 °C and 42 °C, respectively. These results are very much below the critical temperature criteria and this shows that RN release due to failure of containment is highly unlikely for this scenario, even if all uncertainties have not yet been assessed. The details of the fire impact analysis described above are provided in Supporting Report 5-7.

ii) TRU waste

The tyre fire scenario for the transport vehicle of TRU waste was assessed in a similar manner, using the heat generation rate applied for the case of HLW shown in Figure 5.4-6. Only waste package B containers were assessed, but findings are assumed to be similar for waste package A.

As noted previously, bituminised waste in Gr.3 is assumed stable at normal temperatures. However, at temperatures > 180 °C to 200 °C, nitrate reaction with bitumen is autocatalytic, potentially leading to a runaway thermal reaction [6] and therefore this waste was targeted for assessment of fire scenarios.

Figure 5.4-9 shows the distribution of temperature on the surface of the deck and transport cask calculated in a similar manner to the HLW case.

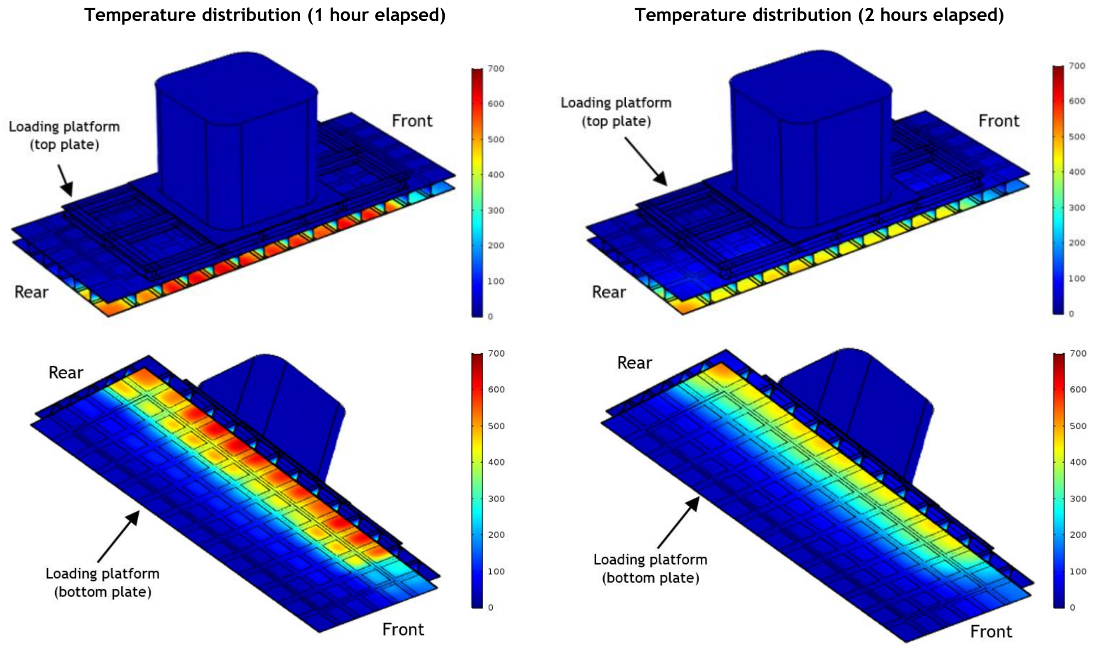

Figure 5.4-9 Temperature distribution of the truck deck during a tyre fire (TRU waste) Since tyres burn only on the right side, major temperature rise is limited to the area above them. Colour legend shows temperature in °C

Heat input to the transport cask was at most 4 kW. This value was higher than that of the case of HLW shown in Figure 5.4-8, because the surface of the transport cask is closer to the edges of the deck, but was again significantly smaller than heat input to the bottom of the deck (Figure 5.4-6) for the same reasons as the HLW case. Similarly, although the lower surface of the deck is in contact with the flames and has a temperature of up to about 640 °C, the upper deck temperature increases only up to ≈ 80 °C.

The normal radiogenic heat production of bituminised waste is negligibly small (< ≈ 1 W, see Supporting Report 2-4), and therefore the initial temperature was assumed to be 30 °C, equivalent to the ambient rock temperature at a depth of 500 m. The analysis continued until 12 hours although heat generation effectively ends at 1.5 hours (see Figure 5.4-6). Figure 5.4-10 shows changes in the maximum temperature of the transport casks, waste packages, and bitumen matrix based on this analysis.

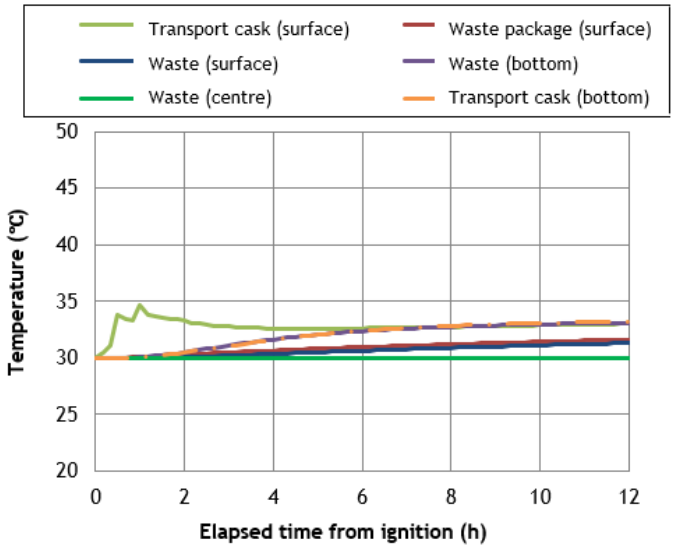

Figure 5.4-10 Temperatures at various positions as a function of fire duration (TRU waste)

The surface of the transport cask reaches a maximum temperature of 35 °C approximately 1 hour after the fire and, thereafter, gradually decreases towards ambient temperature. The temperature of the waste package and contained bitumen gradually increases, but the rate of increase slows after 12 hours. Thus, the temperature rise of the bitumen is far lower than the runaway temperature. For details of this fire assessment, see Supporting Report 5-8 (but it should be noted here that a more thorough assessment of fires will likely be needed in the future).

(3) Explosions

As mentioned in Section 5.4.1 (3), Both monitoring and counter-measures (e.g., sufficiently high ventilation rates, flammable gas catalytic oxidisers) will be implemented to reduce the risk of a gas explosion to the extent possible. Nevertheless, especially given that relatively high methane inflow is experienced in some tunnels in Japan (e.g., at the Horonobe URL), methodology is being developed to assess the consequences of such an abnormal operation scenario. It should be emphasised, however, that here focus is on illustration of how models could be applied to a highly simplified scenario, rather than consideration of how realistic the scenario (and hence interpretation of results) may be.

For this evaluation of a gas explosion, it is assumed that methane concentration in a tunnel results from outgassing from the host rock, and increases due to the failure of the ventilation equipment. It is assumed that such a problem is not picked up by monitoring and/or counter-measures cannot be implemented, possibly due to common mode failure of detection/alarm equipment, loss of access, etc.

As a worst case, ignition from an unspecified source leads to an explosion in a disposal tunnel, which occurs under the condition of a methane/air mixing ratio that maximises its explosive power. This explosion then impacts a HLW overpack that is sitting on the floor of the tunnel. For the specified H12V emplacement option, such overpacks would be within a transport container until lowered into the disposal hole, but the more complex analysis required for this case will be introduced only in the future.

The maximum speed of the overpack displaced by the worst-case explosion was calculated to be 20 m/s by numerical analysis of the blast wave. An elasto-plastic analysis was then performed, assuming that the overpack collides with the tunnel wall surface at this speed. As shown in Figure 5.4-11, the equivalent plastic strain exceeded the breaking strain near the surface of the overpack at the collision point, but the deformation of the inner surface of the overpack was within the elastic region, so no through-cracks should occur. Details of this impact assessment are given in Supporting Report 5-9.

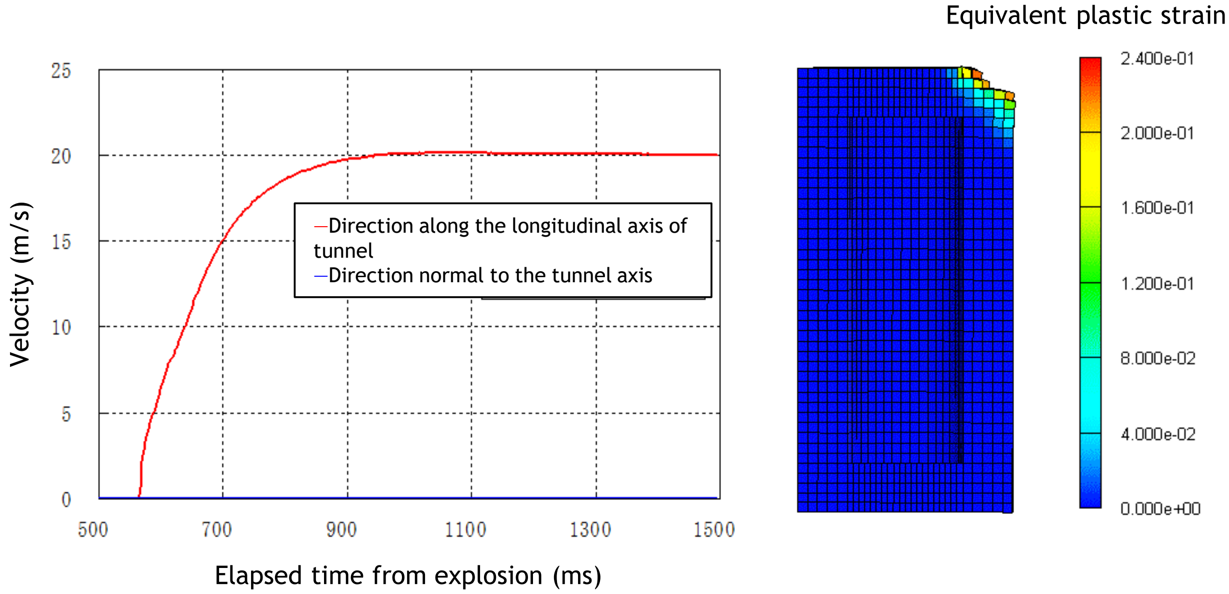

Figure 5.4-11 Results of impact analysis for a methane gas explosion scenario

This calculation was carried for the H12-V concept, but could readily be applied to the PEM option. Nevertheless, it is clear that the consequences for the PEM would be significantly less due to its greater mass and the protection of the overpack by the PEM handling shell and surrounding buffer. In the future, a priority will be to assess explosion risks for TRU waste, for which case explosive gasses produced from the waste packages themselves (mainly hydrogen and methane) would also need to be considered. In all cases, gas explosion impact assessments will aim to be more realistic and provide feedback to design that improves resilience – decreasing both the probability of such abnormal states and the consequences should one occur.

(4) Loss of power

Based on Section 5.4.1 (4), an illustrative scenario for loss of ventilation cooling of the HLW buffer store is assessed here. During buffer storage immediately after unloading of a transport cask, 28 canisters of HLW may be present and loss of ventilation will result in temperature increases. Thermal analysis was conservatively conducted by assuming heat generation of 559 W per HLW canister (i.e. after 30 rather than 50 years interim storage).

Figure 5.4-12 shows that the temperature rises rapidly until 5 days after loss of ventilation, and reaches about 200 °C at the surface of the waste. Thereafter, the temperature rise significantly slows down, reaching a plateau of about 210 °C after about 30 days. This temperature is much lower than the sensitisation temperature (450 to 850 °C) [18] and melting point (1,398 to 1,427 °C) [15] of austenitic stainless steel and hence damage of the HLW canister and RN release is extremely unlikely. In addition, the centre temperature of the HLW is sufficiently below the devitrification temperature limit of 610 °C [16] [17] that this is not a concern. The details of this analysis are given in Supporting Report 5-10.

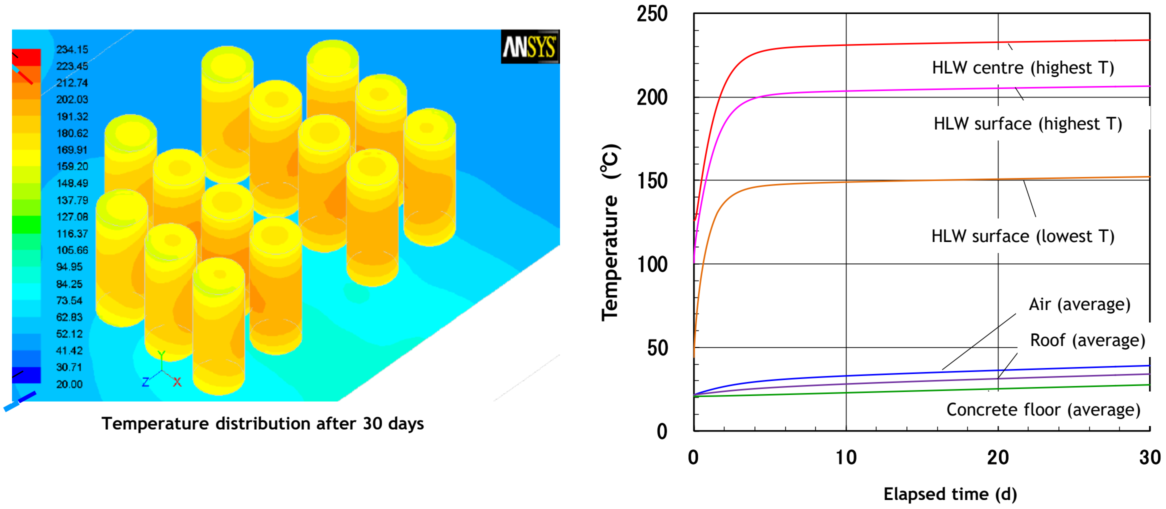

Figure 5.4-12 Assessment of temperature rise of HLW due to loss of buffer store ventilation

In the case of TRU waste, as shown in Supporting Report 2-4, the highest heat generation rate results from Gr.4 waste (glass melting furnaces) at ≈ 60 W/container. This heat generation rate is thus small compared with the HLW (about 10%). Further, only 8 containers are assumed to be received in one transportation shipment and thus there is no need of temporary storage before inspection. A moderate temperature rise is possible in the case of loss of ventilation, but currently this is considered to have negligible safety impacts, although will be more rigorously assessed at a later date.

(5) Assessment of equipment malfunction scenarios

As noted in Section 5.4.1 (5), the case of the runaway of the ramp transport vehicle due to a failure of its braking system is chosen as an assessment example. Even with the conservative assumption that all abnormal state counter-measures fail, collision speeds were determined to be insufficient to damage the overpack severely due to a penetration crack [19].

The actual speed at the time of collision in a runaway scenario needs to be set on a site- and design-specific basis, taking into consideration the length of possible runaway sections and the effects of any catch lanes, arresters, etc. These counter-measures will be specified in the future, as part of the repository design of access ramps for specific sites.

5.4.3 Potential for radionuclide release from the repository

A wide range of abnormal operation scenarios were assessed with a focus on the potential failure of containment and resulting RN release. Partial deformation by the force of drops was noted, but sufficient damage to the overpack (or waste package) that could lead to RN release is considered to be unlikely. In addition, even if the temperature of HLW or TRU waste is elevated due to fires or failure of ventilation cooling, current analyses suggest it is insufficient to give a risk of thermal damage.

For the specific case of PEM emplacement, the PEM shell and buffer material provide additional mechanical and thermal protection of the overpack compared to the H12V case.

In the future, in order to enhance the reliability of the assessment, more detailed equipment designs will be developed based on actual site environmental conditions, allowing development and evaluation of a more complete range of perturbation scenarios.

5.5 Mitigation of, and recovery from, accidents

According to the assessment results in Section 5.4, the properties of the waste itself, primary containers and, after encapsulation, overpacks or disposal packages with considerable physical and thermal resistance, makes any loss of RN containment very unlikely, even under abnormal operational conditions.

Even if unlikely, it is important to consider any credible scenario that could potentially result in RN releases. Mitigation of, and recovery from, significant accidents, whether or not RN releases actually occur, is therefore considered. A perspective on this is provided by the recovery plan [20] developed after the accidents at the US Waste Isolation Pilot Plant (WIPP) site.

5.5.1 Lessons from accidents at WIPP

Within the WIPP facility, two separate accidents occurred in February 2014: a rock-transport vehicle fire and a radiological release from emplaced waste. A summary of the accidents and associated recovery work, based on the reports of US Department of the Environment (DOE) and related research institutes, is given below.

(1) Outline of the WIPP accident

According to the accident investigation report [21], the vehicle fire on February 5, 2014, started near the engine compartment of a truck carrying excavated rock salt. The cause was a leak of oil (lubricating fluid or fuel), which contacted the hot exhaust system and led to ignition. The worker driving the vehicle initially tried to extinguish the fire, without success, and within 10 minutes the front tyre ignited and the fire burned fiercely for 20 to 40 minutes (this sequence of events demonstrates that the fire scenarios analysed by NUMO could indeed occur, but also that propagation of fires from fuel to tyres would need to be considered in the future).

Evacuation of workers from the underground facilities was completed within 50 minutes of detecting the fire. The fire continued to smoulder for about 12 hours, until finally extinguished by a team using foam extinguishing agents. The work zone in which the accident occurred did not handle radioactive waste and thus there was no RN release, but six workers were treated for smoke inhalation.

Independent of the vehicle fire, on February 14, 2014, there was an event in which RNs were released from a drum after emplacement. In this accident, low pH wastes containing nitrate and organic matter, which did not meet the waste acceptance criteria, were mistakenly received and emplaced. After emplacement in the disposal panel, due to a runaway chemical reaction, heat and gas generation occurred, bursting the lid of a drum and causing RN release into the facility [22] [23] [24].

In normal operation, air was not filtered prior to discharge. On the day of the accident, a continuous air monitor detected radioactivity and therefore the system automatically switched to High Efficiency Particulate Air (HEPA) filtration, capable of removing most RN from the exhaust air. As a result, it was possible to prevent a major release to the outside, however a slight increase in the radioactivity in the air was observed outside the facility, due to leakage of valves that redirect ventilation to the filtration system [23].

Due to the radiological release accident, US DOE formulated the WIPP Recovery Plan [20], suspending operations until December 2016 in order to carry out recovery work, such as decontamination of the facilities.

(2) Recovery work

The recovery work at WIPP was carried out in two phases and included the steps below [20].

Recovery Plan - Phase I

- Isolate ventilation flow-through: two bypass dampers, which had allowed limited airflow to bypass HEPA filters, were sealed with high-density foam.
- Monitoring instruments were lowered into the air intake shafts: data from the monitors showed no radiological contamination in the area of the shafts underground and established safety for personnel entry.
- Recovery teams entered and surveyed conditions to establish two usable egress locations — a requirement for future underground work. The teams confirmed communications with the surface base station and established an underground base of operations.
- Recovery teams surveyed conditions further, moving towards the suspected release location and identified a breached waste container. A Technical Assistance Team of experts was established to review photos and video, as well as analyse samples of debris, in order to determine the cause of the release.
- Contaminated filters were replaced: for operations to continue, a properly functioning ventilation system was required and hence two filtration units were replaced.

Recovery Plan - Phase II

- Mitigate the contamination source: this was accomplished according to a plan developed from the knowledge gained during Phase I.
- Restore conditions that will support operations: this includes equipment for radiological monitoring, ground stabilisation activities (e.g., bolting) for mine safety, equipment and systems maintenance, cleaning, and upgrades.
- Incorporate corrective actions: lessons learned from the fire and RN event are used to enhance programmes and procedures prior to resuming operations.

In parallel with the above recovery work, identification of the causes of the accidents was carried out and results were disseminated on a website [25]. It is noted that the root causes were fundamentally due to failures of waste production/characterisation QA and waste acceptance testing – in turn resulting from poorly defined regulations and acceptance criteria, together with weaknesses in staff training and safety culture. Corrective actions are compiled as a safety assessment report [26], where the following improvements are described:

- Fire protection measures (maintenance and inspection of equipment used in non-radiation work, installation of automatic fire extinguishing equipment, etc.).
- Emergency response plan (continuous assessment of emergency response requirements, education and training of workers, etc.).
- Waste confirmation (approval of wastes on reception, confirmation of certified waste,

etc.).

5.5.2 Mitigation and recovery plans for a Geological Disposal Facility (GDF)

Based on the assessment results shown in Section 5.4.2, RN releases are unlikely in the perturbation scenarios examined but, considering the WIPP experience summarised in Section 5.5.1, the installation of an emergency ventilation system is considered prudent as a measure to mitigate the effects of any RN release that could possibly occur (see Section 4.5.6 (6)). In addition, conditions not relevant to WIPP, like the need for drainage management, should also be considered.

If RN leakage occurs, recovery using the following procedure can be considered, referring to the WIPP Recovery plan.

- Contain the released RNs within the facility.
- Implementation of measures to prevent the spread of contamination (ventilation and drainage).
- Sharing and disseminating information on accident.
- Investigation of the site where the accident occurred and confirmation of radiological release, identification of the cause of the accident.
- Formulation of a recovery work plan.
- Establishment of a response base for the recovery work; training and education of a remediation team in the recovery work.
- Recovery of damaged waste.
- If there is contamination, decontamination of the contaminated area.
- Confirmation of site recovery.

Detailed mitigation and recovery plans will be specified in the future when formulating operational plans based on specific site conditions and then, as shown in Section 5.6.2 (3), relevant accident response techniques will be developed.

5.6 Summary and future perspective

5.6.1 Key findings of this chapter

This chapter focussed on the assessment of potential radiological consequences during the operational period of a repository, based on the repository designs and operational processes developed in Chapter 4 and with reference to guidelines and regulations for safety assessment of similar facilities handling radioactive materials. Key findings in this chapter are summarised as:

- In assessment of normal operation scenarios, the annual effective dose to the public was below the 50 μSv/y target, due to appropriate design of shielding and distance to the facility boundary.
- Abnormal condition scenarios were assessed using event-trees describing the transition of perturbations to abnormal states that may damage the waste and cause loss of containment. The assumed abnormal operations are classified as drops, fires, explosions, loss of power and other equipment malfunctions. The robustness of waste containment was assessed under the conservative assumption that design counter-measures fail.

- Even under abnormal operational conditions, the containment system described was shown to be sufficiently robust, given the fundamental safety measures incorporated into the design, such as limitation of handling heights. No scenario considered in the current study led to damage that would result in RN release.

Based on the above results, the likelihood of occurrence of an accident that releases RNs from the facility design developed in Chapter 4 is assessed to be extremely small. Nevertheless, the preliminary stage of this operational safety assessment must also be noted. Several issues should be further explored, as noted in Section 5.6.2, and the assessment will also need to be updated when the repository designs are further developed.

5.6.2 Future perspective

To improve the confidence in operational safety assessment, key R&D issues noted in Table 5.6-1 will be considered further.

Table 5.6-1 Major future technical efforts related to operational safety

Classification	Main action items
Operational safety assessment Scenario construction	• Construction of scenarios that include complex event chains, such as common-mode failure • Hazard database update
Development of operational safety assessment technology	• Acquisition of important data to support safety evaluation • Evaluation methodology for complex events
Development of accident response technology	• Examine measures to deal with accidents and associated recovery

(1) Development of scenarios for operational safety assessment

Although illustrative abnormal operation scenarios were developed in this chapter, assuring comprehensiveness of scenarios is key to improving the confidence in assessments required for tailoring repository design to given site environments. In particular, single failure modes were investigated, while multiple failure modes or common mode failure scenarios need to be developed and analysed to support detailed design of both the repository and associated operational processes. Furthermore, specific perturbations with potentially large impacts (e.g. flooding) have been identified that would justify a more thorough assessment.

The procedure of scenario development needs to be coupled to continuous reviews of incidents in relevant environments, to reduce as much as possible the risk of completely unexpected abnormal states (sometimes termed “black swans”), which is a lesson learned from many abnormal states in the past. A review of relevant international and domestic experience of abnormal states will be performed and results recorded in a database, as part of a structured operational safety knowledge management system. The combination of such a database and constant review of details of scenarios will help to ensure their comprehensiveness.

Finally, it is noted that conventional accidents during repository construction are very important hazards to consider in repository development, but this is not formally seen as a component of operational safety from the nuclear regulatory perspective covered in this Chapter. Instead, actions to handle requirements related to workers protection are identified as a future action in Section 4.8.3 (2) (ii).

(2) Development of analytical methods for operational safety assessment

The mechanical analyses of drops and collisions, together with the thermal analyses of fires, are critical to the assessment of operational robustness presented in this chapter. Verification of the analytical codes, quality assurance of models and data used and the validation of analytical results are all required. In particular, for validation, full scale simulation of relevant drops and fires need to be carried out under relevant conditions.

Although this chapter focussed on radiological safety, conventional safety of any workers present in radiation-controlled areas will also need to be assessed for the abnormal conditions noted. If a fire occurs underground, for example, damage to facilities and equipment may be significant, leading to risks to workers. For such cases, the applicability of analytical models of fires underground will be investigated, based on best international practice.

(3) Development of mitigation and recovery techniques

As shown in Section 5.5, decontamination plans will be developed for scenarios of perturbations that could lead to RN contamination. Lessons learned from accidents, such as those in the WIPP facility [20], will be used (although it is recognised that site and repository conditions will be different in Japan). For example, the design of the underground facility layout and key supporting infrastructure specifically aimed to minimise the impact of such accidents may be effective as a mitigation measure. Nevertheless, it will be necessary to establish and document recovery procedures and to develop required technology, especially for actions carried out by remote control.

In addition, in terms of the treatment of any waste subject to perturbed conditions, criteria to determine the necessity of recovery or required treatment thereafter will be considered in the future.

Supporting Reports (SRs)

SR 5-1	Evaluation of direct irradiation and skyshine from the HLW surface facility
SR 5-2	Evaluation of direct irradiation and skyshine from the TRU waste surface facility
SR 5-3	Evaluation of HLW overpack impacts
SR 5-4	Evaluation of TRU waste package impacts
SR 5-5	Assessment of fuel fires
SR 5-6	Evaluation of tyre fires
SR 5-7	Impact of a tyre fire on HLW overpacks
SR 5-8	Impact of a tyre fire on TRU waste packages
SR 5-9	Calculations of physical impact by a methane gas explosion
SR 5-10	Evaluation of temperature rise in the HLW buffer store due to loss of ventilation

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6 POST-CLOSURE SAFETY ASSESSMENT

In this chapter, the assessment will be developed based on representative Site Descriptive Models (SDMs) for host rocks that might result from site selection, as established in Chapter 3, together with tailored repository designs, as developed in Chapter 4. Based on consideration of the latest developments in science and technology, this assessment forms the basis for discussion of safety after repository closure. This aims to confirm past generic demonstrations of the fundamental feasibility of safe geological disposal in Japan and show that, when candidate sites are identified, the scientific and technological foundation for carrying out the required safety assessment is in place.

In Section 6.1, as a prerequisite for the basic safety assessment concept described in Chapter 2, the reference inventory of radioactive waste and the design specifications of the repository are presented. The basic framework of risk-informed safety assessment is then described, utilising a classification of scenarios based on their probability and setting corresponding dose and risk targets for specified assessment timescales. Section 6.2 explains the systematic methodology of evaluation developed, based on an internationally recognised approach to safety assessment. Using this methodology, in Section 6.3, post-closure safety of repositories tailored to the SDMs is examined, illustrating the development of representative scenarios and setting analysis cases to quantify their radiological consequences. In Section 6.4, the analytical models, calculation codes and data sets used are explained and calculated doses presented. In Section 6.5, the method of stylisation and the calculated results of dose and risk are described for the special case of scenarios involving human intrusion. Finally, in Section 6.6, a summary of the assessments is presented and required future efforts to improve such assessments are identified.

6.1 Basic framework of safety assessment

6.1.1 Safety assessment procedure

The methodology of safety assessment is well established, based on research and development in advanced national programmes and general guidance provided by international organisations [1] [2]. The work flow used here is summarised as follows:

- Characterisation of the geological environment conditions at a site expected to possess the required safety functions (Chapter 3); repository design considering such conditions (Chapter 4); leading to creation of a bounding range of scenarios of future evolution.
- Modelling to quantitatively analyse the behaviour of the repository system (already partly discussed in Chapter 4, but further assessed in this Chapter), based on defined scenarios and associated parameter sets (these are referred to as analysis cases in this report).
- Based on the analysis cases, selecting analytical models and datasets to quantify radionuclide (RN) migration and release to the biosphere. Determination of the resulting post-closure radiological effects (doses, risks and other factors) and comparison with safety regulations as the basis for assessment of safety.

The timescales for evaluation (see Section 6.1.4), as required for safety assessment, along with target dose and risks limits for specific classes of scenario (see Section 6.1.5), provide the standards for discussing safety and are generally based on established regulations. As noted in Chapter 2, safety regulations for geological disposal in Japan will be established in the future. In this report, therefore, preliminary assumptions are made based on recommendations by international organisations and safety regulations for similar facilities in Japan.

In the H12 and TRU-2 reports, the geological environments commonly observed in Japan are represented generically by typical examples of crystalline and sedimentary rocks. The required demonstrations of fundamental feasibility for both HLW and TRU waste are assured by highly robust engineered barriers and a sufficiently conservative safety evaluation. However, in this report, the safety assessment methodology is intended to be a template for that carried out during future site selection (i.e. to be further developed in coming stages). For this reason, more realistic SDMs for representative host rocks that are widely distributed in Japan were developed in Chapter 3. Site-specific repository designs take specific SDM features into consideration, supported by an analysis that treats their characteristics as realistically as practicable, while still maintaining overall conservatism in the safety assessment. For this reason, based on R&D progress since the H12 and TRU-2 reports, special consideration is given to the following points:

- In order to appropriately deal with spatial and temporal uncertainty in the behaviour of the repository, scenarios have been developed where both probability of their occurrence and the magnitude of associated impacts to be assessed are decoupled. The framework of the safety assessment thus introduces risk-informed thinking as part of the evaluation.

- In order to ensure that the repository design is properly adapted to the given SDM characteristics, the engineered barrier system (EBS) components, repository design and layout are tailored to the spatial distribution of safety-relevant features, in particular faults, fractures and other major structures in the host rock (as described in Chapter 4). Scenarios, models and datasets to assess groundwater flow and RN migration behaviour aim to reflect a reasonable description of the behaviour of the repository.

- In order to ensure both the transparency and reliability of the safety assessment results, efforts are made to improve traceability of the scenario development process, facilitating assessment of comprehensiveness of treatment and adequacy of models and datasets.

6.1.2 Prerequisites for safety assessment

Safety assessment prerequisites, which provide a foundation for all subsequent evaluations, include the SDMs, associated repository designs and the inventory of radioactive waste.

(1) Geological repositories

In Chapter 3, SDMs are defined for plutonic rocks, together with Neogene and Pre-Neogene sediments. For each, the SDM illustrates the geological setting along with associated distributions of thermal, hydraulic, mechanical and geochemical characteristics. In particular, with regard to groundwater chemistry characteristics that affect both evolution of the EBS and RN release/migration, two types of model waters are defined (hereinafter referred to as low salinity and high salinity). In Chapter 4, two variants of EBS design for the disposal of high-level radioactive waste (HLW) are presented, an upgraded option for the vertical emplacement assessed in H12 ("H12V") and an alternative horizontal emplacement of a pre-fabricated EBS module ("PEM"). For TRU waste disposal, emplacement vault geometry is adapted to the rock mechanical conditions of the SDM, with two variants of the disposal waste package (A and B: see Section 4.4.2 (2) (ii)). These variants, summarised in Table 6.1-1, are referred to as the plutonic, Neogene and Pre-Neogene repositories.

Table 6.1-1 Potential repository host rocks subject to safety assessment

<table>
<tr><th>Geological environment model</th><th colspan="2">Repository design
(co-location of HLW and TRU waste)</th></tr>
<tr><td rowspan="4">Plutonic repository:
• Low salinity
• High salinity</td><td rowspan="2">HLW</td><td>H12V</td></tr>
<tr><td>PEM</td></tr>
<tr><td rowspan="2">TRU (Gr.1, Gr.2, Gr.3, Gr.4H, Gr.4L)</td><td>Package A</td></tr>
<tr><td>Package B</td></tr>
<tr><td rowspan="4">Neogene repository:
• Low salinity
• High salinity</td><td rowspan="2">HLW</td><td>H12V</td></tr>
<tr><td>PEM</td></tr>
<tr><td rowspan="2">TRU (Gr.1, Gr.2, Gr.3, Gr.4H, Gr.4L)</td><td>Package A</td></tr>
<tr><td>Package B</td></tr>
<tr><td rowspan="4">Pre-Neogene repository:
• Low salinity
• High salinity</td><td rowspan="2">HLW</td><td>H12V</td></tr>
<tr><td>PEM</td></tr>
<tr><td rowspan="2">TRU (Gr.1, Gr.2, Gr.3, Gr.4H, Gr.4L)</td><td>Package A</td></tr>
<tr><td>Package B</td></tr>
</table>

Gr.: Group

Table 6.1-2 shows the components of the repository considered when conducting safety assessment, although not all are explicitly assessed at the present time.

Table 6.1-2 Repository components considered in the safety assessment

Component	H12V					PEM				TRU (Gr.1, Gr.2, Gr.4HD, Gr.4HH)					TRU (Gr.3, Gr.4LD, Gr.4LC)				
	DT	MT	CT	AR	AS	DT	MT	CT	AR	DT	MT	CT	AR	AS	DT	MT	CT	AR	AS
HLW: Glass waste matrix	✓					✓													
HLW: Overpack	✓					✓													
HLW: PEM handling shell						✓													
HLW/TRU: Buffer	✓					✓				✓									
TRU: Waste matrix										✓					✓				
TRU: Waste package container										✓					✓				
TRU: Infill for waste package										✓					✓				
TRU: Infill between waste packages										✓					✓				
TRU: Structural framework										✓					✓				
Tunnel/vault: Grout	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	
Tunnel/vault: Steel support	*	*	*	*		*	*	*		*	*	*	*		*	*	*	*	
Tunnel/vault: Shotcrete	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	
Tunnel/vault: Rock bolt	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	
Tunnel/vault: Concrete liner		✓	✓	✓	✓		✓	✓	✓	*	✓	✓	✓	✓		✓	✓	✓	✓
Tunnel/vault: Invert concrete	*	*	*	✓		✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	
Tunnel/vault: Central drain										✓					✓				
Tunnel/vault: Drain	✓	✓	✓	✓		✓	✓	✓			✓	✓	✓			✓	✓	✓	
Tunnel/vault: Waterproof sheet	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	
Tunnel/vault: Backfill material	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Plug: Mechanical plug	✓					✓					✓					✓			
Plug: Permeable layer (crushed rock)	✓					✓					✓					✓			
Plug: Filter material (glass fibre)	✓					✓					✓					✓			
Plug: Drain pipe	✓					✓					✓					✓			
Plug: Embedded form (glass fibre reinforced cement)	✓					✓					✓					✓			
Plug: Hydraulic plug (mixed bentonite and silica sand)			✓	✓	✓		✓	✓	✓			✓	✓	✓			✓	✓	✓

DT-Disposal tunnel; MT-Main tunnel; CT-Connecting Tunnel; AR-Access ramp; AS-Access shaft, ✓: Constituent elements of repository considered for all host rocks. *: Considered only for Neogene sediments. Gr.4HD: Gr.4H (drum), Gr.4HH: Gr.4H (container as yet not specified – MHHRW – miscellaneous higher heat reprocessing waste), Gr.4LD: Gr.4L (drum), Gr.4LC: Gr.4L (box container).

Table 6.1-2 includes components introduced in the construction and operation of the repository, which are also included in the Features, Events and Processes (FEPs) (NUMO FEP list) described in Section 6.3.2 (1). The three repositories are illustrated in Figures 6.1-1, 6.1-2 and 6.1-3. In this report, explanation is focussed on the plutonic rock repository, with direct reference to the other rocks in cases where there are clear differences in features related to the geological environment and associated repository design.

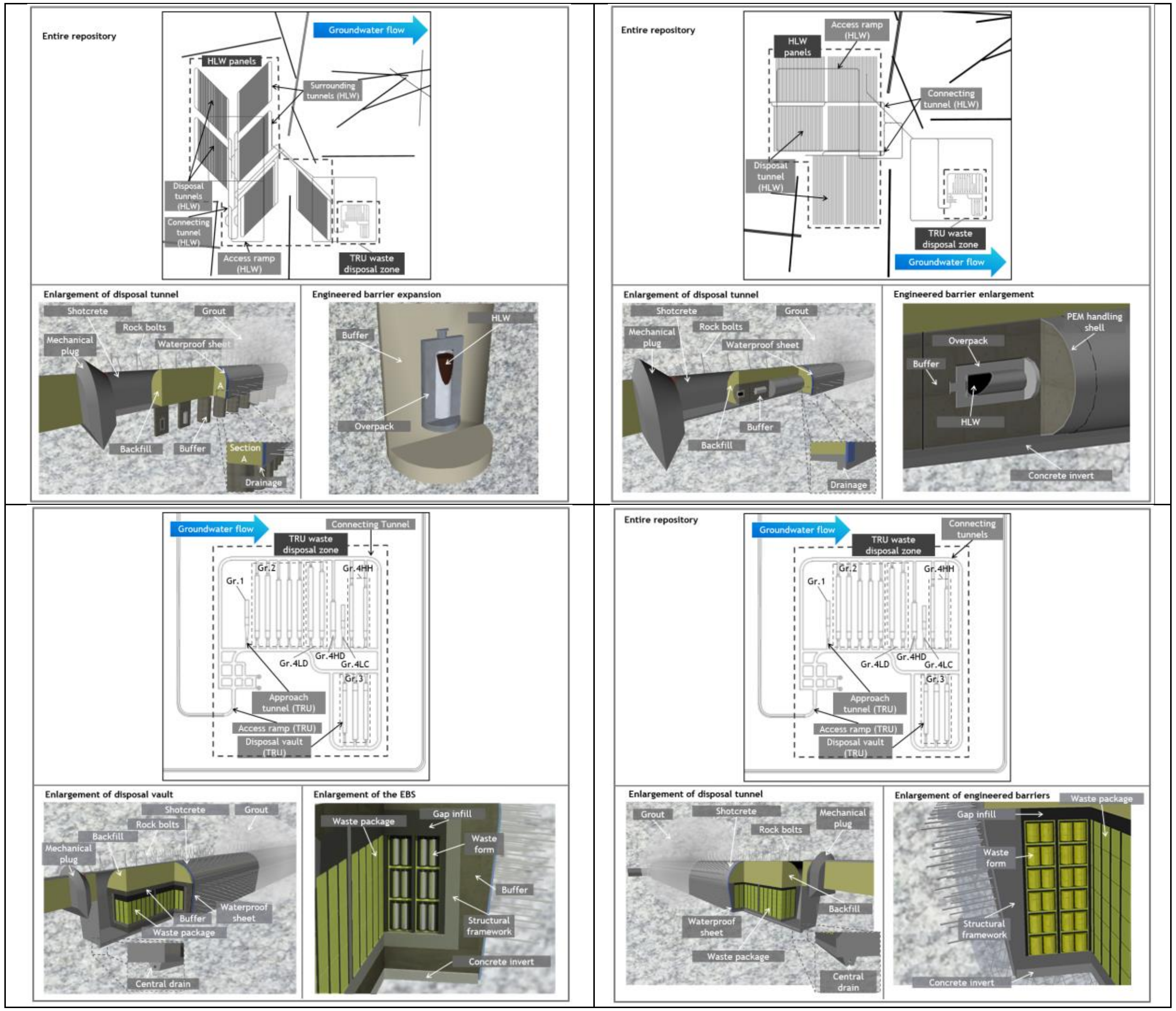

Figure 6.1-1 Illustration of components of the plutonic rock repository.
Top left HLW (H12V), top right HLW (PEM), bottom left TRU (Gr.2), bottom right TRU (Gr.3)

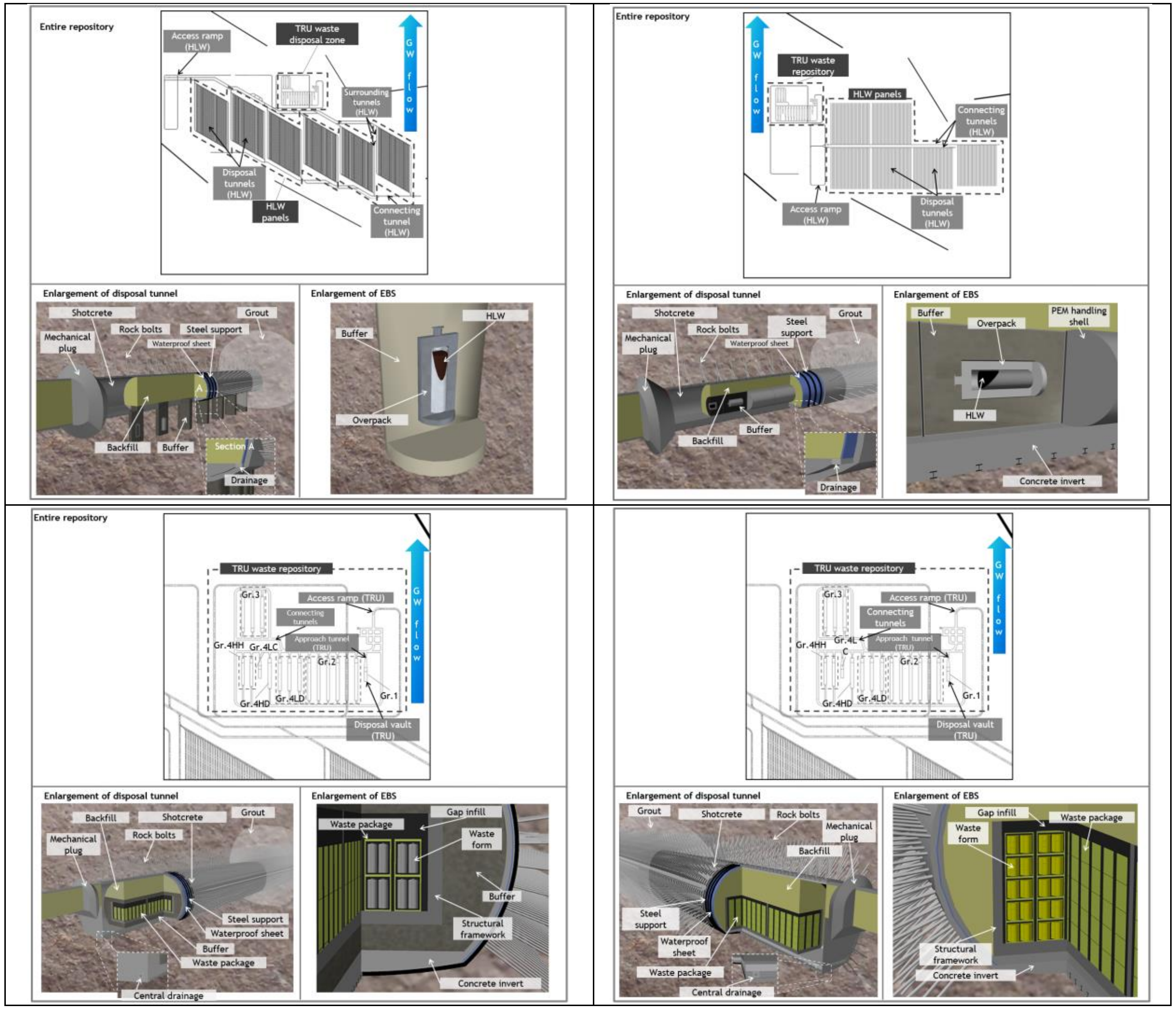

Figure 6.1-2 Illustration of components of the repository of Neogene repository.
Top left HLW (H12V), top right HLW (PEM), bottom left TRU (Gr.2), bottom right TRU (Gr.3)

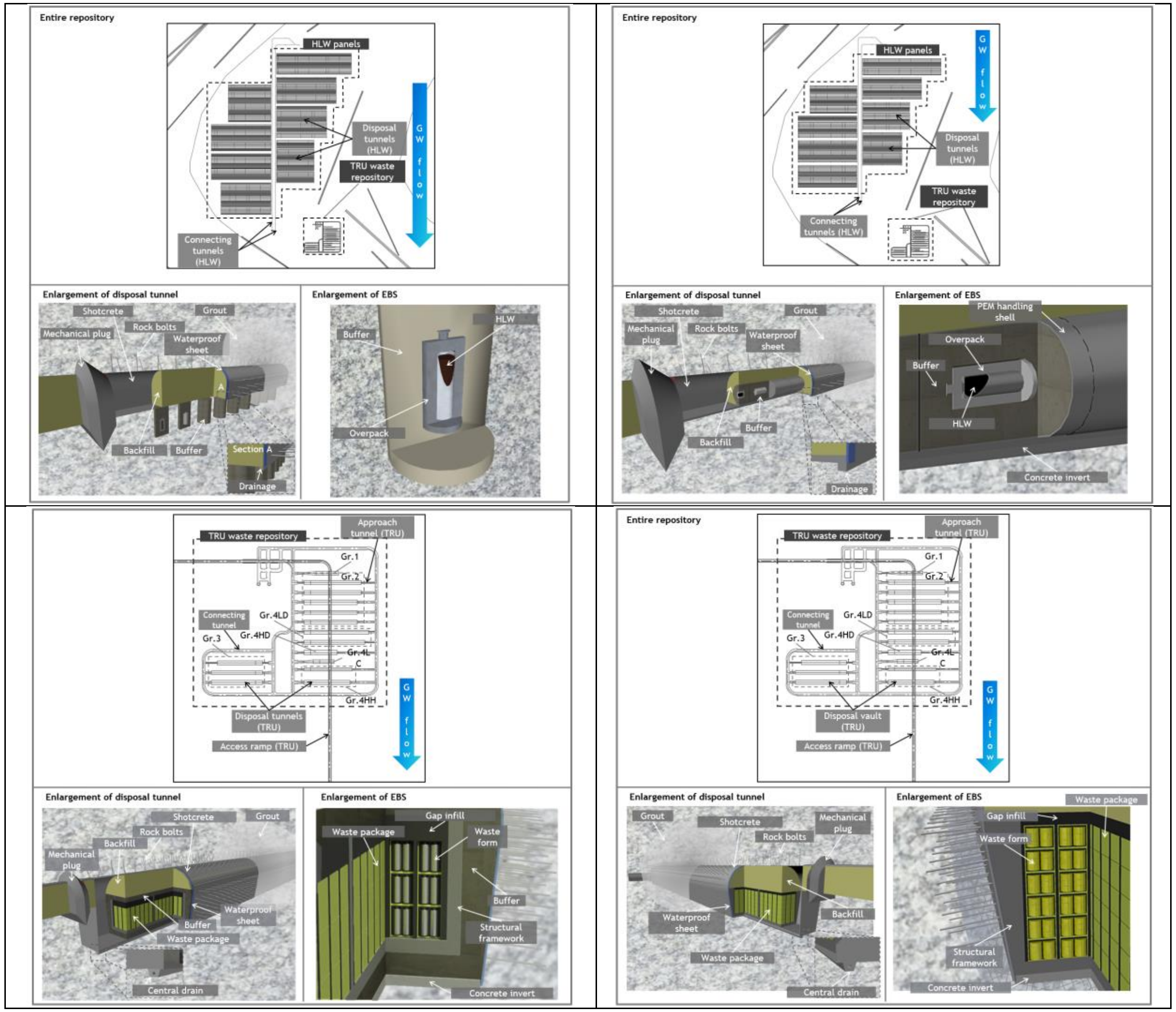

Figure 6.1-3 Illustration of components of the Pre-Neogene repository.
Top left HLW (H12V), top right HLW (PEM), bottom left TRU (Gr.2), bottom right TRU (Gr.3)

(2) Radionuclides to be evaluated and radioactivity inventory

The specifications of radioactive waste allocated for geological disposal in Japan are given in Chapter 2. These include a wide range of fission products and activation product RNs, many of which do not need to be taken into account when considering long-term radiological influences due to short half-life and/or low concentration. Here, the process of selecting RNs for post-closure release and transport analysis will be described. For further details, see Supporting Report 2-3. Selection of the RNs that are considered in the biosphere evaluation when calculating dose conversion factors is also described (see Supporting Report 6-1).

(i) Selecting relevant RNs for HLW

With reference to domestic and foreign safety assessments since the H12 report [3] [4] [5] [6] [7] [8] [9], there is consensus that post-closure analysis focuses on a limited number of RNs, having half-lives longer than a certain period, provided that short-lived parent RNs in decay chains are included in the source term and short-lived daughters in the biosphere assessment. The selection of such RNs depends on the safety assessment scenarios involved (see Section 6.1.5 (2)).

Specifically, with reference to selection methods in other countries, RNs having a half-life of more than 6 months were initially extracted from the 1,252 RNs listed by ICRP (International Commission on Radiological Protection) [10]. For scenarios involving RN transport via groundwater, target RNs are based on those selected both in the H12 report and by implementing agencies of other countries that dispose of HLW and/or spent fuel (SF). Primary concern in safety assessments focuses on RNs that are highly soluble with low sorption onto either engineered barriers or geosphere transport paths [11]. Thus, C-14, Cl-36, and I-129 were newly added to the list of potentially important RNs to be included in the analysis. Pd-107 and Sm-151 were excluded due to expected low importance, with reference to the RNs dominating doses assessed in recent studies reported by other countries. However, it is understood that the selection of RNs is preliminary and might need reassessment in coming studies.

For low probability and human intrusion scenarios that may occur at an early stage (see Sections 6.4.3 and 6.5), the RNs Sr-90 and Cs-137, which have relatively short half-lives but very high initial inventories, were added. A decision was made to add also RNs of the actinide decay series with high importance in terms of internal exposure.

Since HLW disposal occurs only after a period of 30 to 50 y interim storage after production, the radioactivity of 40,000 packages (reference inventory) at the time of closure of the repository will represent a distribution of actual ages; however this distribution is uncertain at present. In this report, as described in Section 4.2.2 (1), the repository is designed on the premise of a 50 y HLW interim storage. Furthermore, conservatively, the time for decay during the operational period of the repository is not considered. Thus, post-closure safety assessment assumes an age of 50 y for all waste packages. However, considering that containment by the overpack is > 1 ky, the inventory of RNs for safety assessment after overpack failure is relatively insensitive to this value.

Table 6.1-3 shows the radioactivity per glass block for the selected RNs after 50 y interim storage (see Supporting Report 2-3).

Figure 6.1-4 shows the decay chains for the actinides considered in the release and migration analysis.

Table 6.1-3 Selected radionuclides and inventories for safety assessment (HLW)

Nuclide	Half-life (y)	Inventory (Bq/unit)	Nuclide	Half-life (y)	Inventory (Bq/unit)
C-14	$5.7x10^{3}$	$1.2x10^{8}$	**U-234**	$2.5x10^{5}$	$9.8x10^{7}$
Cl-36	$3.0x10^{5}$	$4.8x10^{8}$	**U-235**	$7.0x10^{8}$	$3.0x10^{6}$
Se-79	$3.0x10^{5}$	$3.2x10^{9}$	**U-236**	$2.3x10^{7}$	$4.6x10^{7}$
Sr-90	2.9x10	$8.2x10^{14}$	**U-238**	$4.5x10^{9}$	$3.9x10^{7}$
Zr-93	$1.5x10^{6}$	$7.2x10^{10}$	**Np-236**	$1.5x10^{5}$	$2.3x10^{5}$
Nb-93m	1.6x10	$6.4x10^{10}$	**Np-237**	$2.1x10^{6}$	$1.4x10^{10}$
Nb-94	$2.0x10^{4}$	$1.5x10^{8}$	**Pu-236**	2.9	$2.9x10^{4}$
Tc-99	$2.1x10^{5}$	$5.2x10^{11}$	**Pu-238**	8.8x10	$5.4x10^{11}$
Sn-126	$2.3x10^{5}$	$1.1x10^{10}$	**Pu-239**	$2.4x10^{4}$	$6.8x10^{10}$
I-129	$1.6x10^{7}$	$3.8x10^{7}$	**Pu-240**	$6.6x10^{3}$	$3.3x10^{11}$
Cs-135	$2.3x10^{6}$	$1.8x10^{10}$	**Pu-241**	1.4x10	$2.2x10^{12}$
Cs-137	3.0x10	$1.2x10^{15}$	**Pu-242**	$3.8x10^{5}$	$4.2x10^{8}$
Pb-210	2.2x10	$7.6x10^{2}$	**Pu-244**	$8.0x10^{7}$	$1.3x10^{2}$
Ra-226	$1.6x10^{3}$	$1.6x10^{3}$	**Am-241**	$4.3x10^{2}$	$3.5x10^{13}$
Ra-228	5.8	3.3	**Am-242m**	$1.4x10^{2}$	$2.0x10^{11}$
Ac-227	2.2x10	$8.8x10^{4}$	**Am-243**	$7.4x10^{3}$	$8.1x10^{11}$
Th-228	1.9	$5.6x10^{6}$	**Cm-243**	2.9x10	$1.9x10^{11}$
Th-229	$7.3x10^{3}$	$1.1x10^{4}$	**Cm-244**	1.8x10	$1.4x10^{13}$
Th-230	$7.5x10^{4}$	$8.7x10^{4}$	**Cm-245**	$8.5x10^{3}$	$1.7x10^{10}$
Th-232	$1.4x10^{10}$	3.3	**Cm-246**	$4.8x10^{3}$	$2.8x10^{9}$
Pa-231	$3.3x10^{4}$	$1.1x10^{5}$	**Cm-247**	$1.6x10^{7}$	$1.1x10^{4}$
U-232	6.9x10	$5.5x10^{6}$	**Cm-248**	$3.5x10^{5}$	$3.4x10^{4}$
U-233	$1.6x10^{5}$	$3.0x10^{6}$			

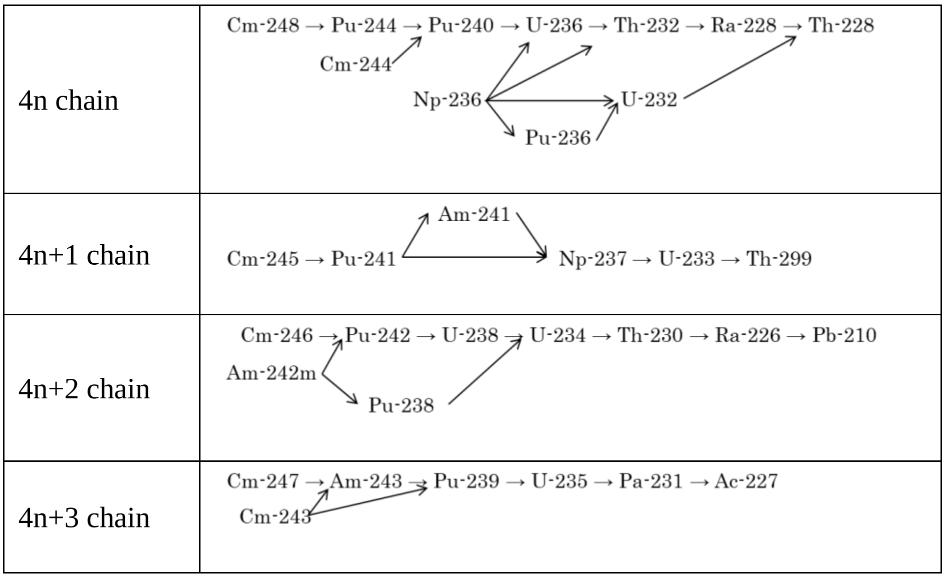

Figure 6.1-4 Relevant actinide decay series for RN migration analysis

(ii) Selecting relevant RNs for TRU waste

The process for TRU waste is basically the same as HLW, but complicated by much greater uncertainties regarding the characteristics and volumes of future arisings [12] [13]. For this reason, it was decided to select the RNs to be evaluated based on the latest information on those targeted for the TRU-2 safety assessment [14].

A further complication for TRU waste is its inherent variability in RN concentrations, which is much greater than for vitrified HLW. Therefore, it is also difficult to justify referring to the RNs of interest in the safety assessment carried out for long-lived L/ILW in other countries (which has similarities to Japanese TRU waste), as done in Section 6.1.2 (2) (i) above. Therefore, in this report, in addition to the RNs selected for the TRU-2 groundwater release scenarios and other perturbation scenarios that involve release via groundwater (e.g., human intrusion), it was decided to add isotopes of the actinide decay series with high importance for internal exposure.

Currently, there is no specified requirement for interim storage of TRU waste prior to disposal. Thus, the TRU-2 assumption of 25 y storage after production is taken as a reference, resulting in an approximately one order of magnitude decrease in heat output, due to decay of short-lived isotopes. Specifically, the radioactivity inventory at the time of closure used in this report considers radioactive decay for 25 y after production [13] for all waste packages. As some existing TRU waste has already been stored for over 25 y, actual radioactivity inventories may be significantly lower. Table 6.1-4 shows the selected RNs[1] and estimated values of their inventory for each waste group (see Supporting Report 2-3). Gr.4 is classified into two groups: low heat (4L) and high heat (4H) based on thermal output; these in turn are further sub-classified by waste container (see Sections 4.4.2 and 4.5.4, giving 4LD and 4LC, 4HD and 4HH; Table 6.1-2). For RN migration analysis, the radioactivity inventory is separately specified for each of these TRU waste groups, so that the dose can be calculated individually. The same actinide decay chains are used as for vitrified HLW (Figure 6.1-4).

[1] Pd-107 was excluded from the RNs evaluated for HLW, but TRU is more diverse and, since this isotope is subject to safety evaluation in the TRU-2 report, it is also considered in this report.

Table 6.1-4 Selected radionuclides and inventories for safety assessment (TRU waste) (1/2)

Group classification		Group 1	Group 2			Group 3	Group 4			
			Hulls and ends	CSD-C	CSD-B		Low heat		High heat	
Abbreviation		Gr.1	Gr.2	Gr.2	Gr.2	Gr.3	Gr.4L		Gr.4H	
							Gr.4LD	Gr.4LC	Gr.4HD	Gr.4HH
Container		200 l drum	Stainless steel canister	Stainless steel canister	Stainless steel canister	200 l drum	200 l drum	Box container	200 l drum	MHHRW
Number of units		1,673	27,522	3,780	30	27,441	24,076	287	4,587	1,188
Volume (m^3)		335	5,342	734	7	5,492	4,845	884	921	458
Nuclide	Half-life (y)	Radioactivity (Bq)								
C-14	5.7×10^{3}	0.0	4.8×10^{14}	1.1×10^{14}	7.5×10^{7}	7.4×10^{12}	3.4×10^{9}	2.4×10^{9}	5.3×10^{11}	2.2×10^{12}
Cl-36	3.0×10^{5}	0.0	9.2×10^{12}	0.0	3.0×10^{8}	3.3×10^{11}	3.6×10^{7}	1.1×10^{6}	2.2×10^{4}	1.3×10^{7}
Co-60	5.3	1.3×10^{5}	5.1×10^{16}	2.2×10^{16}	6.8×10^{9}	4.6×10^{11}	3.8×10^{15}	1.5×10^{10}	3.1×10^{12}	1.3×10^{13}
Ni-59	1.0×10^{5}	5.5×10^{3}	7.5×10^{15}	0.0	8.3×10^{8}	4.8×10^{8}	5.9×10^{13}	7.2×10^{5}	8.2×10^{5}	4.1×10^{8}
Ni-63	1.0×10^{2}	7.2×10^{5}	9.5×10^{17}	1.7×10^{17}	0.0	5.6×10^{10}	7.4×10^{15}	8.2×10^{7}	9.5×10^{7}	4.8×10^{10}
Se-79	3.0×10^{5}	3.9×10^{5}	2.2×10^{12}	1.0×10^{12}	2.8×10^{10}	6.7×10^{9}	1.3×10^{11}	1.8×10^{9}	3.9×10^{11}	1.6×10^{12}
Sr-90	2.9×10	3.6×10^{10}	1.9×10^{17}	1.2×10^{17}	4.2×10^{14}	6.8×10^{14}	1.2×10^{16}	1.6×10^{14}	3.5×10^{16}	1.5×10^{17}
Zr-93	1.5×10^{6}	1.8×10^{6}	3.0×10^{14}	6.8×10^{13}	0.0	3.1×10^{10}	7.6×10^{12}	1.6×10^{10}	1.7×10^{12}	7.3×10^{12}
Nb-94	2.0×10^{4}	3.3×10^{6}	2.6×10^{15}	0.0	0.0	1.9×10^{6}	3.9×10^{7}	8.0×10^{5}	1.2×10^{8}	5.2×10^{8}
Mo-93	4.0×10^{3}	3.7×10	5.6×10^{13}	0.0	0.0	8.1×10^{6}	5.4×10^{7}	2.5×10^{6}	5.3×10^{8}	9.0×10^{7}
Tc-99	2.1×10^{5}	0.0	6.5×10^{14}	4.3×10^{13}	7.2×10^{11}	3.9×10^{11}	3.4×10^{12}	5.6×10^{10}	1.2×10^{13}	9.7×10^{13}
Pd-107	6.5×10^{6}	1.1×10^{5}	5.5×10^{11}	0.0	0.0	2.5×10^{9}	3.1×10^{10}	4.0×10^{9}	1.0×10^{11}	4.2×10^{11}
Sn-126	2.3×10^{5}	7.4×10^{5}	3.8×10^{12}	0.0	0.0	1.1×10^{10}	2.3×10^{11}	3.3×10^{9}	7.0×10^{11}	2.9×10^{12}
I-129	1.6×10^{7}	5.9×10^{13}	1.6×10^{11}	1.0×10^{11}	3.9×10^{7}	7.2×10^{11}	1.1×10^{8}	1.0×10^{7}	1.5×10^{9}	3.0×10^{9}
Cs-135	2.3×10^{6}	4.3×10^{5}	2.2×10^{12}	1.3×10^{12}	2.8×10^{10}	7.0×10^{9}	3.1×10^{11}	1.9×10^{9}	4.1×10^{11}	1.7×10^{12}
Cs-137	3.0×10	5.3×10^{10}	2.8×10^{17}	1.4×10^{17}	1.5×10^{15}	8.6×10^{14}	3.8×10^{16}	2.4×10^{14}	5.0×10^{16}	2.1×10^{17}
Pb-210	2.2×10	2.5×10^{-1}	1.6×10^{5}	5.1×10^{4}	8.9×10	3.0×10^{4}	3.1×10^{5}	2.8×10^{3}	2.8×10^{5}	7.2×10^{3}
Ra-226	1.6×10^{3}	1.1	8.1×10^{5}	3.0×10^{5}	4.4×10^{2}	1.4×10^{5}	1.5×10^{6}	1.3×10^{4}	1.3×10^{6}	3.6×10^{4}
Ra-228	5.8	2.2×10^{-4}	8.6×10^{2}	2.9×10^{-1}	3.6×10^{-1}	2.4×10	1.1×10^{2}	2.5	1.8×10^{2}	5.7

Table 6.1-4 Selected radionuclides and inventories for safety assessment (TRU waste) (2/2)

Group classification		Group 1	Group 2			Group 3	Group 4			
			Hulls and ends	CSD-C	CSD-B		Low heat		High heat	
Abbreviation		Gr.1	Gr.2	Gr.2	Gr.2	Gr.3	Gr.4L		Gr.4H	
							Gr.4LD	Gr.4LC	Gr.4HD	Gr.4HH
Container		200 l drum	Stainless steel canister	Stainless steel canister	Stainless steel canister	200 l drum	200 l drum	Box container	200 l drum	MHHRW
Number of units		1,673	27, 522	3,780	30	27,441	24,076	287	4,587	1,188
Volume (m^3)		335	5,342	734	7	5,492	4,845	884	921	458
Nuclide	**Half-life(y)**	**Radioactivity (Bq)**								
Ac-227	2.2×10	2.5	1.0×10^{7}	9.8×10^{2}	9.4×10^{3}	2.9×10^{5}	5.3×10^{6}	2.9×10^{4}	3.9×10^{6}	6.4×10^{4}
Th-228	1.9	1.9×10^{-4}	7.4×10^{2}	2.3×10^{-1}	3.0×10^{-1}	2.0×10	9.5×10	2.1	1.5×10^{2}	4.8
Th-229	7.3×10^{3}	5.5×10^{-4}	1.3×10^{7}	9.2×10^{4}	5.8×10^{4}	9.3×10^{3}	1.2×10^{5}	9.6×10^{2}	1.0×10^{5}	2.7×10^{5}
Th-230	7.5×10^{4}	2.2×10^{2}	1.8×10^{8}	8.1×10^{7}	9.1×10^{4}	2.7×10^{7}	2.8×10^{8}	2.5×10^{6}	2.5×10^{8}	7.8×10^{6}
Th-232	1.4×10^{10}	3.2×10^{-4}	1.3×10^{3}	5.4×10^{-1}	5.2×10^{-1}	3.5×10	1.6×10^{2}	3.7	2.7×10^{2}	8.3
Pa-231	3.3×10^{4}	8.1	3.2×10^{7}	4.4×10^{3}	3.0×10^{4}	9.2×10^{5}	1.7×10^{7}	9.2×10^{4}	1.3×10^{7}	2.1×10^{5}
U-233	1.6×10^{5}	7.8×10^{-1}	5.4×10^{9}	7.8×10^{7}	4.9×10^{7}	6.2×10^{6}	8.6×10^{7}	6.1×10^{5}	7.2×10^{7}	2.3×10^{8}
U-234	2.5×10^{5}	1.0×10^{6}	1.1×10^{12}	6.8×10^{11}	5.3×10^{8}	1.4×10^{11}	1.3×10^{12}	1.2×10^{10}	1.2×10^{12}	5.4×10^{10}
U-235	7.0×10^{8}	1.5×10^{4}	6.1×10^{10}	1.7×10^{7}	5.7×10^{7}	1.7×10^{9}	3.2×10^{10}	1.7×10^{8}	2.4×10^{10}	3.9×10^{8}
U-236	2.3×10^{7}	2.6×10^{5}	1.0×10^{12}	8.7×10^{8}	4.2×10^{8}	2.8×10^{10}	1.3×10^{11}	3.0×10^{9}	2.2×10^{11}	6.7×10^{9}
U-238	4.5×10^{9}	2.2×10^{5}	8.6×10^{11}	2.5×10^{4}	1.3×10^{9}	2.4×10^{10}	1.6×10^{11}	2.5×10^{9}	2.0×10^{11}	5.5×10^{9}
Np-237	2.1×10^{6}	1.7×10^{4}	1.4×10^{12}	7.4×10^{11}	4.5×10^{11}	4.7×10^{10}	7.0×10^{11}	3.8×10^{9}	5.2×10^{11}	2.1×10^{12}
Pu-238	8.8×10	2.3×10^{9}	8.9×10^{15}	8.7×10^{15}	3.5×10^{12}	5.1×10^{14}	3.5×10^{15}	2.9×10^{13}	2.6×10^{15}	7.7×10^{14}
Pu-239	2.4×10^{4}	2.4×10^{8}	9.7×10^{14}	6.8×10^{14}	1.3×10^{12}	5.7×10^{13}	8.7×10^{14}	3.0×10^{12}	4.8×10^{14}	8.6×10^{12}
Pu-240	6.6×10^{3}	3.7×10^{8}	1.5×10^{15}	1.2×10^{15}	1.7×10^{12}	8.9×10^{13}	1.0×10^{15}	4.8×10^{12}	6.2×10^{14}	3.6×10^{13}
Pu-241	1.4×10	2.9×10^{10}	1.0×10^{17}	8.5×10^{16}	3.3×10^{9}	3.1×10^{16}	3.8×10^{16}	1.6×10^{14}	3.6×10^{16}	6.3×10^{14}
Pu-242	3.8×10^{5}	1.6×10^{6}	6.4×10^{12}	6.5×10^{12}	4.5×10^{9}	3.7×10^{11}	2.4×10^{12}	1.9×10^{10}	2.0×10^{12}	9.4×10^{10}
Am-241	4.3×10^{2}	3.0×10^{9}	1.1×10^{16}	8.1×10^{15}	2.9×10^{13}	2.4×10^{15}	4.8×10^{15}	2.1×10^{13}	3.9×10^{15}	4.7×10^{15}
Am-242m	1.4×10^{2}	6.6×10^{6}	2.3×10^{13}	0.0	0.0	7.1×10^{11}	4.6×10^{13}	3.3×10^{12}	5.8×10^{14}	4.4×10^{15}
Am-243	7.4×10^{3}	1.8×10^{7}	6.9×10^{13}	1.7×10^{15}	3.0×10^{11}	5.5×10^{11}	1.2×10^{13}	2.2×10^{11}	1.5×10^{13}	1.1×10^{14}
Cm-244	1.8×10	8.1×10^{8}	3.1×10^{15}	2.9×10^{15}	5.1×10^{12}	1.3×10^{12}	5.0×10^{14}	9.7×10^{12}	6.7×10^{14}	5.0×10^{15}
Cm-245	8.5×10^{3}	2.2×10^{5}	8.6×10^{11}	0.0	3.5×10^{9}	2.1×10^{9}	1.4×10^{11}	2.7×10^{9}	1.8×10^{11}	1.4×10^{12}

(iii) Selecting relevant RNs for biosphere assessment

The biosphere assessment in this report treats RN migration near the surface of the Earth and assesses resultant radiation exposure to humans in the same manner as in the H12 report. From defined hydraulic characteristics of surface waters and relevant food chains, it is possible to assess radiation exposure to human beings from a defined release from the geological environment (at the geosphere biosphere interface - GBI). It is assumed that transfer of RNs within biosphere exposure pathways is much faster than release and transport through the geological environment [15].

In terms of handling decay of RNs in the biosphere, previous studies have illustrated methods for both treating daughter RNs in secular equilibrium with their parents [4] [16] [17] [18] [19] or individually, with cut-off half-lives of 1 month [20] or 25 days [3] [14] [21] [22]. Based on these references, and in order to assure that all relevant RNs are considered, in this report, RNs with half-lives of 25 days or more were evaluated individually. Thus, in addition to the RNs mentioned in (i) and (ii) above, decay series daughters are also considered. In this case, for daughters with half-lives of 25 days or more, dose conversion factors were determined individually. For daughters with half-lives of less than 25 days, it is assumed that they migrate in secular equilibrium with a longer-lived parent and the effective dose conversion factor of the daughter is added to that of the parent. RNs selected for biosphere evaluation are listed in Table 6.1-5. For details of the selection process, see Supporting Report 6-1.

Table 6.1-5 Selected radionuclides for biosphere assessment

Nuclide	Half-life (y)	Nuclide	Half-life (y)
C-14	5.7×10^{3}	**Pa-233**	7.4×10^{-2}
Cl-36	3.0×10^{5}	**U-232**	6.9x10
Co-60	5.3	**U-233**	1.6×10^{5}
Ni-59	1.0×10^{5}	**U-234**	2.5×10^{5}
Ni-63	1.0×10^{2}	**U-235**	7.0×10^{8}
Se-79	3.0×10^{5}	**U-236**	2.3×10^{7}
Sr-90	2.9x10	**U-238**	4.5×10^{9}
Zr-93	1.5×10^{6}	**Np-236**	1.5×10^{5}
Nb-93m	1.6x10	**Np-237**	2.1×10^{6}
Nb-94	2.0×10^{4}	**Pu-236**	2.9
Mo-93	4.0×10^{3}	**Pu-238**	8.8x10
Tc-99	2.1×10^{5}	**Pu-239**	2.4×10^{4}
Pd-107	6.5×10^{6}	**Pu-240**	6.6×10^{3}
Sn-126	2.3×10^{5}	**Pu-241**	1.4x10
I-129	1.6×10^{7}	**Pu-242**	3.8×10^{5}
Cs-135	2.3×10^{6}	**Pu-244**	8.0×10^{7}
Cs-137	3.0x10	**Am-241**	4.3×10^{2}
Pb-210	2.2x10	**Am-242m**	1.4×10^{2}
Po-210	3.8×10^{-1}	**Am-243**	7.4×10^{3}
Ra-226	1.6×10^{3}	**Cm-243**	2.9x10
Ra-228	5.8	**Cm-244**	1.8x10
Ac-227	2.2x10	**Cm-245**	8.5×10^{3}
Th-228	1.9	**Cm-246**	4.8×10^{3}
Th-229	7.3×10^{3}	**Cm-247**	1.6×10^{7}
Th-230	7.5×10^{4}	**Cm-248**	3.5×10^{5}
Th-232	1.4×10^{10}		
Pa-231	3.3×10^{4}		

Dose calculation is based on the geosphere release and migration analysis of RNs selected in Sections 6.1.2 (2) (i) and (ii) above, which defines input at the GBI at specific times. The impact of this flux is then assessed by multiplying RN fluxes in groundwater by isotope-specific dose conversion factors, which are defined for relevant biosphere environments, see Section 6.4.1 (6).

6.1.3 Treatment of spatial scales

The SDMs in Chapter 3 and the repository designs in Chapter 4 consider different spatial scales. In the safety assessment, several spatial scales are also considered (see Chapter 2, Section 2.2.4) in a pragmatic and consistent manner. Key scenarios considered when evaluating the safety of the repository involve RNs in the waste dissolving into groundwater and moving through the geological environment until they eventually reach the biosphere (See Section 6.3). In order to rigorously calculate potential doses from such scenarios, simulation of the three-dimensional (3D) spread of RNs from each individual waste package through the engineered barriers and the geological environment to the GBI is required.

The large-scale, 3D RN migration model has to consider characteristics of both the engineered and natural barriers that impact solute transport. Heterogeneities, which exist at all spatial scales, play a key role in such migration. For groundwater flow, as discussed in Section 3.2.2, a nested model can be used that allows the impacts of smaller features to be averaged out at larger scales: these large-scale models provide external boundary conditions, with smaller features considered explicitly only in smaller scale models. For solute transport, however, such simplification is not valid because the microscale features of the flow path completely dominate quantification of effective retardation. Although computer technology is developing rapidly, detailed simulation of RN migration on a kilometre scale while capturing retardation-relevant features on a scale of centimetres or millimetres is not yet feasible.

Therefore, as described in Chapter 2, the concept of nested SDMs to cover multiple spatial scales is taken over for safety assessment and the uncertainties thus introduced discussed explicitly.

(1) Near field scale

The “near field” scale PA model includes the EBS, the disposal tunnels/vaults and a surrounding 100 m of the host rock. This is tailored to the analytical code Partridge [23], which was developed to simulate the detailed composition, shape and size of the engineered barriers and emplacement tunnels/vaults. Information on the heterogeneity of the rock would be relatively detailed at the time of repository implementation due to surveys during excavation (e.g. spatial distribution and hydraulic conductivity characteristics of water-conducting fractures, as shown in Section 3.3.3 (3), and fine structure of solute transport pathways, shown in Section 3.3.3 (4)), allowing analysis of RN release and migration in three dimensions. This makes it possible to identify differences in RN containment performance (for example, as a function of the engineered barrier design), allowing feedback to the design team as required. However, since the current models are relatively simple, it is recognised that these allow only limited feedback on some aspects of disposal concepts. For feedback on details of the design, more elaborate near field models will certainly be needed in the future and this is identified as an R&D goal.

(2) Panel scale

For computational reasons, a larger “panel” scale (several hundred metres by several hundred metres) is also used with the aim of analysing RN migration from an entire disposal panel of the HLW repository (as shown in the designs of Chapter 4) or, in the case of TRU waste, the entire disposal zone. This utilises the output of the near field scale model, which only covers a few tunnels, to assess influences of larger-scale facility design, such as layout of disposal tunnels, major access tunnels and other required infrastructure, together with a range of larger dimension host rock characteristics.

(3) Repository scale

At the “repository” scale (several km x several km), RN migration analysis covers the entire repository, i.e. both the TRU and HLW zones (area: ≈10 km^2) plus several hundred metres of surrounding host rock. Thus, the performance of the repository can be evaluated to assess impacts of both design features (e.g. tunnel and vault plugs) and the retardation capacity of the host rock, over an area greater than that covered by the near field and panel scale models.

(4) Regional scale

At the “regional” scale (tens of km x tens of km, or more depending on the setting), releases from the repository scale model are put in context of the entire flow path from the repository to the GBI. This is based on a general methodology [24] for analysing groundwater flow and solute transfer at such a scale, which makes it possible to estimate site-specific information such as RN retardation and dispersion over the entire flow path. This then provides evaluations of the safety functions expected for specific geological environments. However, it is understood that this approach may not fully capture the nature of the flow field in a heterogeneous host rock and more elaborate tools for capturing flow and RN migration will be considered in the future.

The basic idea of nested spatial scales for RN migration analysis as described above can be widely used, regardless of the stage of the project. This will allow investigations at specific sites to be gradually refined. It is also possible to flexibly respond to the quality and quantity of information and the evolving design of the repository, iteratively improving the resulting safety evaluation.

In view of the current situation, including uncertainties in the SDMs and the limitations of both analytical models and computer capacity, a pragmatic approach to release and migration modelling was established (see Section 6.4).

6.1.4 Treatment of evaluation period

A consideration of uncertainties that increase with time contributes towards setting the time scale for the safety evaluation [25]. As noted in Chapter 2, safety regulations defining the period during which quantitative evaluations are required have been established in many countries: in many of these cases, a time frame of 1 My is adopted (e.g. [26] [27] [28]). In Japan, safety regulations will be set in the future and, currently, no safety assessment timescales are defined. Thus, in this report, with an aim of understanding the behaviour of repositories in specific SDMs in the same way as the generic H12 and TRU-2 assessments, it was decided to conduct evaluations in order to determine the time of appearance of the calculated maximum dose (see Supporting Report 6-3 for details). However, it must be understood that the uncertainty in site evolution is very large at times beyond 1 My. The doses calculated for such long time periods must not be interpreted literally, but more as illustrations of the containment function of the repository.

6.1.5 Risk-informed safety assessment and evaluation criteria

(1) Approach based on probability of occurrence of scenarios

In assessing repository safety, it is necessary to consider the various uncertainties resulting from extremely long timescales together with the heterogeneity and large spatial scale of the geological environment. To respond to such uncertainty, scenarios for possible future repository evolution that are as complete as possible are developed along with an assessment of their probability of occurrence. This results in a “risk-informed” approach, which is consistent with that proposed by international agencies [29] and incorporated specifically into regulations in some countries (for example, [26] [28] [30] [31]). Such a risk-informed approach forms the basis of the safety assessment in this report.

There are two major approaches to apply risk-informed thinking: the integrated approach and the dose/stochastic approach [29]. The former quantifies the probability of occurrence of scenarios and derives a total risk by multiplying this by the calculated radiological impact. The latter disaggregates the probability of scenario occurrence, which allows qualitative judgment of this parameter, from the resultant calculated radiological impact. Both options can be used to assure radiological protection, but decoupled dose/probability presentation provides more information to support system assessment and/or decision making [29]. Additionally, for the long-term scenarios required for radioactive waste safety assessment, it is sometimes difficult to justify specifying quantitative probability [32].

In this report, all scenarios are quantitatively analysed based on the evaluation period described in Section 6.1.4, however, assessing associated scenario probability is problematic, especially given the fact sites are not specified at present. Nevertheless, methods to quantify the probability of particular scenarios have been developed in some countries [33] [34] [35] [36] while, for others, probabilities are defined in regulations [28] [30] [37]. The way in which scenario probability is assessed is discussed further below.

(2) Scenario classification and use in safety evaluation

In the chosen disaggregated dose/probability approach, scenarios are classified based on their probability of occurrence, with radiological impact criteria (dose and/or risk) set for each class. These scenarios include “natural processes” and “human intrusion” events [2] [29] [38] [39] [40].

The repository design aims to ensure that radiological impact is significantly less than the dose constraint value of 300 μSv/y recommended for the general public, or the risk[2] constraint value of 1×10^{-5}/y, and that associated radiation protection optimisation has been carried out [29] [38] [42].

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[2] Radiological risk (of cancer or heritable effects) per year from the repository = yearly dose due to scenario (Sv/y) × ICRP 2007 recommended [41] conversion coefficient of dose to risk of 0.057 (/Sv).

Two sets of scenarios are included to cover impacts of natural perturbations. The "base scenario" assume that the repository is designed and constructed on the basis of appropriate site selection and with appropriate consideration of the site geological conditions. These should assure that the expected safety functions can be relied on and reflects the most probable evolution of the repository system. The alternative "variant" scenarios deviate from the base scenario in order to reflect various inherent uncertainties in the evolution of both the geological environment conditions and the repository itself. The variant scenarios should have much lower probability of occurrence than the base scenario in order to justify assessment against a higher dose limit. However, such probabilities have not been strictly quantified as yet.

In this report, analyses of base scenario are called base case; these together provide the foundation for variant scenarios and associated variant analysis cases. The uncertainties captured in the variant scenarios include those associated with the models and datasets used in the base case and also alternative descriptions of the repository and its evolution. These are then reflected in the variant analysis cases.

An overview of the dose and risk constraint standards set in the safety regulations in other countries (refer to Supporting Report 6-3) shows reasonable consistency for scenarios based on natural perturbations: with dose standards set between 10 and 300 μSv/y and risk standards between 10^{-5} and 10^{-6}/y. A risk of 10^{-6}/y corresponds to a dose of about 20 μSv/y. Therefore, 10 μSv/y is the most severe criterion internationally.

In order to evaluate the robustness of the repository system, it is also important to consider very low probability natural perturbations that could significantly affect barrier functions, and also inadvertent human intrusion scenarios [2] [42]. There is, however, less consistency in the way that such scenarios are handled internationally (see Supporting Report 6-3).

As in other international assessments, "what-if scenarios" are also defined, based on assumptions or models that are extremely unlikely or physically impossible, but aim only to improve understanding of the performance (especially robustness) of the repository [1] [2].

Thus, in this report, system evolutions based on natural processes are classified into "base scenario", "variant scenarios" and "low probability perturbation scenarios". In terms of inadvertent human intrusion[3], avoiding areas during site selection where mineral resources with significant economic value exist [43] and disposal at a depth of more than 300 m as stipulated in the Final Disposal Act, should ensure that the probability of occurrence is low.

The following expands on the definition of these scenarios and, in the absence of specific Japanese regulations, discusses relevant comparison values for doses calculated from the resultant RN releases, based on the international norms noted above.

(i) Base scenario

The base scenario reflect what is considered to be the most reasonable representation of evolution of specific geological repositories that are sited, constructed and operated appropriately. These form the basis for judging whether the repository fulfils the stated goal of minimising risks to the human population at all times in the future. For such scenarios, 10

[3] As intentional human intrusion is not assessed in other safety assessments [2] [29] [38] [42], it is also not considered in this report (see Section 6.5).

μSv/y, the most stringent standard applied in the safety regulations of other countries (Supporting Report 6-3), was set as the "target value"[4].

(ii) Variant scenarios

Variant scenario extend the safety arguments developed in the base scenario by taking into consideration safety-relevant uncertainties or alternative assumptions in both the evolution of the geological repository with time and the models and databases used to simulate such evolution. The IAEA [38] and ICRP [42] provide guidance on such scenarios, on the basis that the long-term evolution considers natural perturbations with relatively high probability of occurrence. Based on this, 300 μSv/y (the risk constraint value of ≈ 1 x 10^{-5}/y if the probability of occurrence was one) is recommended as a dose constraint value for this scenario category [38] [42] and is adopted in this report for discussion of safety.

(iii) Low probability perturbation scenario

Low probability perturbation scenario are defined to cover the inherent uncertainty that remains in descriptions of very long timescale evolution, even if site selection and facility design are appropriately carried out. Even if the probability of occurrence of major perturbations is very low, the repository system aims to be sufficiently robust that, even in such cases, there is no major radiological impact.

To assess significance of radiological impacts from such scenarios, the thinking for "disruptive natural events" in geological disposal described by ICRP [42] (based on present existing exposure levels and emergency exposure levels as comparison standards) was followed. Specifically with regard to dose, the range of the reference levels for emergency exposure situations immediately after occurrence (20 to 100 mSv for one year) and for long-term exposure (after the second year: 1 to 20 mSv/y) were set as target values. For these scenarios, risk calculation was also estimated by quantifying the occurrence frequency of the perturbation considered. A target value of 10^{-5}/y was used, which is an internationally recommended value for the sum of the risks of credible scenarios.

(iv) Human intrusion scenario

Inadvertent human intrusion is defined as a possible event that could lead to a significant reduction or loss of safety functions of the geological disposal system. The probability of such occurrence is considered to be low for a repository deeper than 300 m in an area without significant mineral resources, especially given efforts to preserve records and establish warning markers. Therefore, as in the case of the low probability perturbation scenarios, emphasis is on demonstrating repository robustness by showing that there is no major radiological impact.

Regarding human intrusion scenario, the ICRP [42] concludes that there are no scientific grounds for estimating future human activities and their probability of occurrence, and hence it is not appropriate to conduct quantitative evaluations to compare such scenarios with doses or risks. However, in the safety regulations of some countries, there are cases where it is necessary to evaluate the potential impact of future human activities, such as in the UK [37].

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[4] Even if the doses for the base scenario exceed 10 μSv/y, safety can be assured unless the internationally recommended dose-constraint of 300 μSv/y or risk constraint of 10^{-5}/y is exceeded.

In addition, in the safety case report that SKB produced in 2011 to support the license application of a geological repository for spent fuel [44], the impact of stylised human intrusion scenario, including dose to intruders, is calculated but, in accordance with regulation, not included in the risk summation. According to the US Environmental Protection Agency regulation standard [45], the US WIPP operation licence [46] includes human intrusion scenarios as a major focus for safety assessment and quantitatively specifies their probability of occurrence. Based on this background, it was decided to calculate doses and radiological risks for illustrative scenarios, with radiological exposure targets the same as for low probability perturbation scenario.

Table 6.1-6 summarises the scenario classification used in this report.

Table 6.1-6 Safety assessment scenario categories and dose targets

Scenario classification	Definition of scenarios and associated dose targets	Dose target
Base scenario	• Scenario considered to be a reasonable representation of repository evolution • In order to minimise radiation exposure, the dose target is set based on the lowest value used in other countries	10 μSv/y
Variant scenario	• Scenario considering uncertainties in the base scenario • A target is set based on dose constraints for the general public recommended by the IAEA [38] and ICRP [42].	300 μSv/y
Low probability perturbation scenario	• For repositories constructed on the basis of proper site selection and design, scenario of natural perturbations that are considered to be extremely unlikely • For such scenario, to confirm that there is no significant radiological impact, the approach and reference values are based on recommendations made by ICRP [42] for unlikely accident scenario, or the risk constraint value is applied.	20 - 100 mSv (1st year) 1- 20 mSv/y (thereafter)
Human intrusion scenario	• The repository is located and designed so as to minimise the risk of human intrusion. While the probability of such intrusion is very difficult to assess, it is considered appropriate to apply the same radiological exposure target as for low probability perturbation scenario.	20 - 100 mSv (1st year) 1 - 20 mSv/y (thereafter)

In both the H12 and TRU-2 reports, the influence of perturbing phenomena such as uplift/erosion, initial engineering defects, future human activities, etc. are handled as variant scenario, and variations of model and data are included in the base scenario. However, these scenarios were not defined according to a clear risk-informed approach that discussed the probability of each scenario. Therefore, it should be noted that the definitions of scenario categories are different for this report, even though scenario terminology is similar.

6.2 Methodology of safety assessment

6.2.1 Basic procedure of safety assessment

The methodology of safety assessment used in this report is in line with internationally accepted general practice, as described in Section 6.1.1. Specific supporting tasks include consideration of the geological setting at sites selected by appropriate procedures (summarised for the reference host rocks in the SDMs illustrated in Chapter 3) and repository design tailored to provide the required safety functions (in this case, reference designs for each SDM, as shown in Chapter 4).

In this section, following a basic framework described in Section 6.1, a series of tasks proceeding from the construction of scenarios, setting of analysis cases for these scenarios, RN release and migration analyses, to final dose evaluation and discussion of uncertainties will be described. The basic procedure of the safety assessment in this report is shown in Figure 6.2-1. This is basically the same for both HLW and TRU waste disposal.

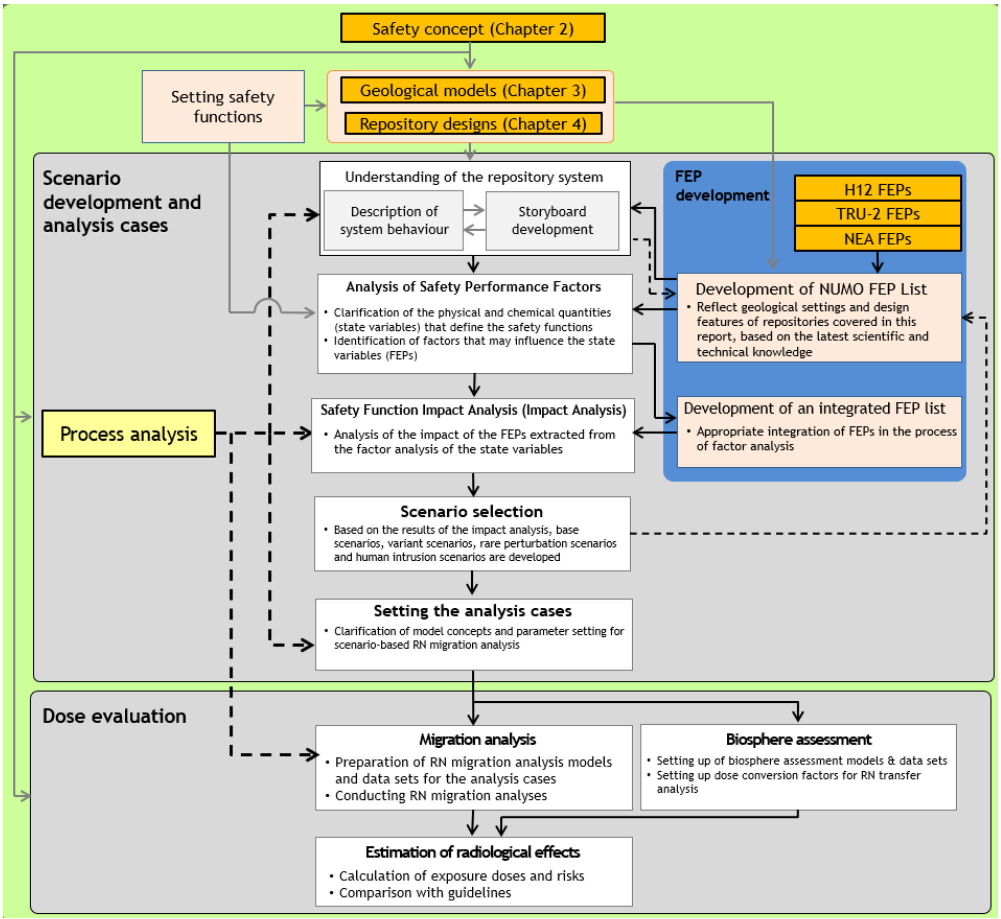


Figure 6.2-1 Basic procedure for safety assessment in this report. The dotted line indicates that the procedure is carried out when required

In order to develop appropriate scenarios, the starting point is usually either a top-level assessment of the temporal changes of the safety functions for a specific site and repository design (termed the “Top-Down” approach [1] [2]), or a comprehensive list of relevant Features, Events and Processes (FEPs) that is used to assemble scenarios (the “Bottom-Up” approach [1] [2]). Here a variant was developed (the “hybrid” approach) for efficiently constructing key scenarios related to repository safety functions, while ensuring comprehensive coverage of all relevant FEPs [47].

In this method, the intended safety functions of a repository that are thought to evolve over the long period of time after closure based on current scientific and technological knowledge is described. In order to properly develop such descriptions, it is necessary to assess the thermal, hydrodynamic, mechanical, and chemical (including biological, if relevant) state

(“THMC state”) of the entire system and how its evolution with time impacts defined safety functions. Therefore, it is necessary to understand THMC state changes of the engineered and geological barriers over all spatial scales for the models discussed in Section 6.1.3 (regional scale/repository scale/panel scale/near field scale) over a time scale that extends from initiation of the repository project and includes recovery of perturbed geological conditions after construction and operation. “Storyboards” have been introduced as an effective method of illustrating such evolution in a way that enables an overview of the scenario and to check the consistency and completeness of the representation of the repository on all relevant time and spatial scales [48]. In order to assess changes in the THMC state for each component FEP (termed “process analysis”), a specific FEP list was created to reflect repository designs in the specific geological environments considered in this report (as described in Chapter 4) based on the latest scientific and technical knowledge (termed the “NUMO FEP list”: see Section 6.3.2 (1)). The NUMO FEP list was reviewed to assure relevance and completeness and used to assure adequacy of description of repository evolution in associated storyboards and resulting scenarios.

The process of development of concrete scenarios can be simply summarised as:

- Clarify physical/chemical quantities (these are referred to as state variables) that define safety functions for each repository component
- Extract and correlate factors considered likely to affect the state variables related to each safety function from each FEP in the NUMO FEP list (referred to as “factor analysis”)
- Based on the factor analysis, integrate relevant FEPs to examine the impact these are likely to have on the state variables (termed “impact analysis”)
- Develop base scenario from the assessed most likely evolution of each repository design considered
- Assess uncertainties and alternative assumptions to develop storyboards for variant scenarios
- Based on understanding of Japanese geology and international recommendations, develop illustrative storyboards for representative low probability perturbation and human intrusion scenarios.

For resulting scenarios, quantitative analysis cases are developed by clarifying specific conditions (such as the models and parameters to be applied) that must be considered in order to quantify radiological impacts. This leads to selection of RN release and migration models and datasets for each analysis case. Finally, these models and datasets are used to calculate radiological impacts (dose or risk), which can be compared with reference values according to the scenario classification, and discussed in order to assess if associated safety targets are met.

This process is covered in more detail in Section 6.3. Subsequently, in Section 6.4, for each analysis case, the required models, calculation codes and datasets for RN release and migration analysis are specified. The biosphere model that defines the RN-specific dose conversion factors for releases to the GBI is also presented. Radiation doses calculated for the base, variation and low probability perturbation scenarios for both HLW and TRU waste in each of the three geological settings, are then presented and discussed.

For human intrusion, special consideration is required to develop representative stylised scenarios: these are presented in Section 6.5 and results of dose assessments then discussed.

6.2.2 Treatment of uncertainty in the safety assessment

In order to carry out the safety assessment according to the methodology described above, it is necessary to comprehensively examine factors influencing safety functions to determine if these could be potentially compromised. Such examination is based on current scientific and technological knowledge of the constituent elements of the repository system, their long-term evolution and potential external disturbances that may occur. However, there is a limit to available scientific knowledge and thus it is necessary to carefully consider handling of resulting uncertainty. Uncertainty arises firstly in scenario definition, associated with the assumed processes causing evolution of the repository. In particular, it is essential to assure that all factors that could potentially adversely affect safety functions are captured. FEPs with a positive impact, but judged as uncertain, are identified but not considered further in the current assessment ("reserve" FEPs that may be utilised in the future to strengthen safety arguments). After that, as discussed in Section 6.1.5, the probability that each scenario will occur has to be determined in order to assign it to a specific class, with any uncertainties in this discussed. These uncertainties will also be key input for the planning of further site characterisation, in order to reduce those related to the SDM.

For the base and variant scenario, there are also uncertainties associated with model assumptions and others arising from constraints of the codes and datasets used. Although the analysis is aimed to be as realistic as possible, for the base scenario the most probable state and states considering associated uncertainty cannot be clearly distinguished. As a result, in the presence of such uncertainties, treatment tends to move towards conservatism (see Section 6.3.3 (2)). Nevertheless, based on future research and development, particularly when sites are specified and safety regulations are defined, a more realistic scenario analysis will be carried out, particularly for the base scenario, allowing them to be more clearly distinguished from variant scenario. In the case of stylised representation of low probability perturbation and human intrusion scenario and associated analysis cases, uncertainties are more fundamental and are emphasised during the discussion of assessment output.

In terms of quantitative estimates of radiological impacts of specific scenarios, total uncertainty results from propagation of all individual contributions from the analysis models and databases used, which can be difficult to quantify. To the extent possible, uncertainties are reduced by rigorous testing (verification and validation) of models and databases, or the impact of these minimised by introducing robustness into the coupled design and safety assessment process. However, all uncertainties cannot be handled in this way and remaining uncertainties need to be described to such an extent that their impact on safety can be assessed. Such analyses will also be essential input to focus future R&D in order to reduce uncertainties. More details on the handling of specific uncertainties are provided during the discussion of setting scenarios and associated analysis cases in Section 6.3.

6.3 Developing scenarios and establishing analysis cases

In this section, development of safety assessment scenarios and setting the associated analysis case for the specific repository designs and SDMs considered in this report is described. Firstly, in Section 6.3.1, the latest knowledge is used to describe the behaviour of the repository after repository closure. Based on this, Section 6.3.2 describes the stepwise procedure for scenario development and the process of collecting and analysing information at each step. Section 6.3.3 describes how analysis cases are set to quantitatively evaluate the radiological impacts of these scenarios.

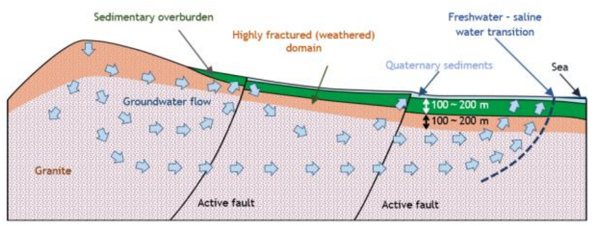
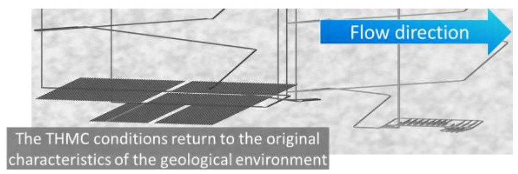
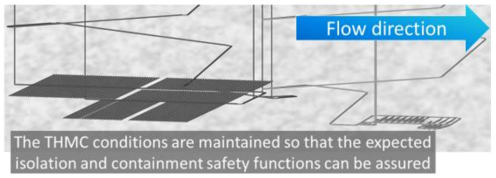
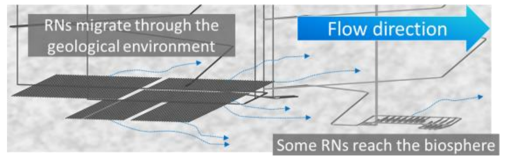
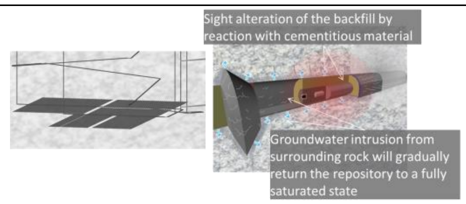
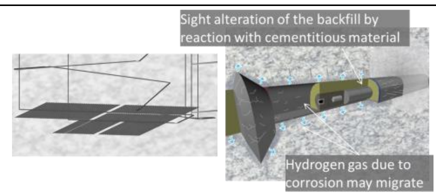
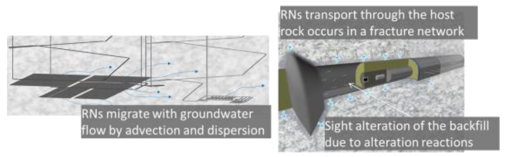
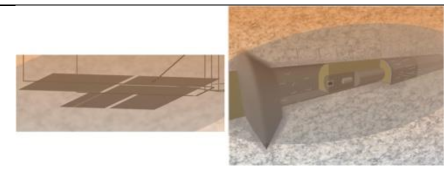
6.3.1 Description of system behaviour after repository closure

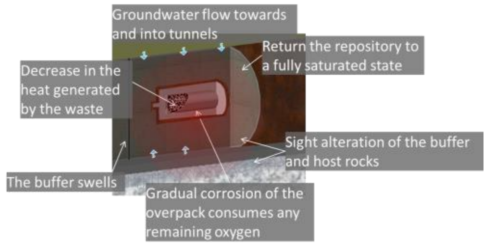
Based on the geological survey technology described in Chapter 3, it can be assured that selected sites will not be significantly influenced by volcanoes, active faults, uplift/erosion, etc., for a long time in the future, while selected representative host rock at depths > 300 m will provide a favourable environment for geological disposal. Based on the characteristics of the host rock, the safety functions of the geological environment are complemented with those of tailored engineered barriers to assure the safety of the repository system, as described in Chapter 4. The post-closure safety functions assigned to the repository as a whole were previously presented in Tables 4.2-4 and 4.2-5. The expected behaviour of the repository system after repository closure, together with resultant release and migration of RNs, can be described and captured in storyboards, as illustrated in Figure 6.3-1 (see Supporting Report 6-11).

In the description of post-closure behaviour of the repository, it is necessary to start with the state of the system at the time of closure, specified as a function of time and space, taking into account the impacts of construction and operation and their possible influence on later RN containment. A common process is used to handle the evolution of different repository designs for the representative host rocks and different types of waste. The resulting storyboards cover specific time steps:

- T_1: period from repository closure until complete re-saturation.
- T_2: period after re-saturation until releases of RNs occur.
- T_3: period after releases of RNs occur, during which the characteristics of the geological environment are considered not significantly changed.
- T_4: period during which the uncertainty regarding characteristics of the geological environment increases significantly with time.

For each of these time steps, the state of the repository safety functions (see Chapter 2) are assessed considering four spatial scales: near field, panel, repository and regional, as previously described in Section 6.1.3. The periods for which safety function for each component is expected to perform is shown in Figure 6.3-2.

	Period during which the current geological environment is expected to be little altered (T1 to T3)				Period during which the uncertainty regarding characteristics of the geological environment increases significantly (T4)
		Period from repository closure until complete re-saturation (T1)	Period after re-saturation until releases of RNs from the EBS (T2)	Period after RN release, when the characteristics of the geological environment are considered not to have significantly changed (T3)	
	Construction & operation	▼ Repository closure	▼ Re-saturation complete	▼ Initiation of radionuclide migration	
Regional scale		・Adequate separation from volcanoes and large active faults ・Very low risk of new faults developing ・Slow, regional processes such as uplift, erosion and sea-level change that gradually alter temperature, hydraulic, stress and chemical fields			・Increased potential for changes in the geological environment to affect the safe function of the repository
Repository scale					
	・Continuous inflow of groundwater into the repository, local flow field towards the repository ・Water table draw down in the repository area as groundwater flows into open tunnels ・Air is drawn into the repository through the access galleries	・The temperature in the vicinity of the repository increases due to the heat generated by the waste, and then decreases in line with radioactivity decay ・Groundwater flow towards and into the repository will continue until completely saturated	・The temperature in the vicinity of the repository gradually decreases and approaches the initial rock ambient value ・The hydraulic field in the vicinity of the repository recovers to its pre-construction state and reaches a steady state ・The initially reducing environment is restored	・The temperature, hydrological, stress and chemical fields in the vicinity of the repository remain in a steady state ・RNs migrate through the geological environment, with advective flow in faults and fractures as the dominant pathway to reach the biosphere	・Changes in the temperature, hydraulic, stress and chemical fields around the repository may occur
Panel scale					
	・Increased temperature in the HLW area ・Decrease in water pressure in the vicinity of tunnels ・EDZ formation around tunnels ・Gaps between backfill and tunnel walls ・Oxidising zone near tunnel walls due to oxygen uptake	・The temperature in the vicinity of emplacement tunnels increases due to the heat generated by the waste, and then decreases in line with radioactivity decay ・Groundwater flow towards and into tunnels will continue until completely saturated ・Tunnel lining is sound and there is no lithostatic pressure on backfill ・EDZ is present in the vicinity of tunnels ・Gaps remain between the backfill and the tunnel walls ・Oxidising areas persist near the tunnel walls ・High alkali content leached from any cementitious materials present and pH of groundwater in the vicinity of the tunnel increases	・The temperature in the vicinity of tunnels gradually decreases and approaches the initial rock ambient value ・The hydraulic field in the vicinity of tunnels recovers to its pre-construction state and reaches a steady state ・The gap between the backfill and the tunnel wall heals due to swelling and deformation of the backfill ・The oxygen in the vicinity of the tunnel wall is gradually consumed by reducing agents such as pyrite, and the environment becomes reducing ・Backfill material and hydraulic plugs are gradually altered by the reactions with groundwater	・The temperature and hydraulic fields in the vicinity of the tunnel are in steady state ・The tunnel support concrete is altered and degraded, and hydraulic conductivity increases. A continuous, highly permeable structure may be formed ・Potential flow short-circuits along tunnels are blocked by hydraulic plugs ・The tunnel deforms due to rock movements ・Reducing environment persists ・RNs migrate with groundwater flow by advection and dispersion	・Changes in the temperature, hydraulic, stress and chemical fields may occur

<table>
<tr>
<td rowspan="2">Near field scale</td>
<td></td>
<td>
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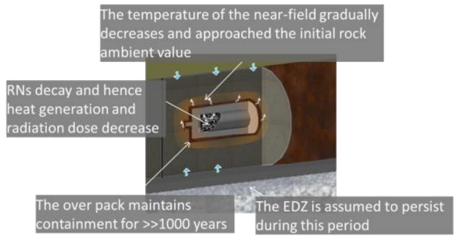
<td>
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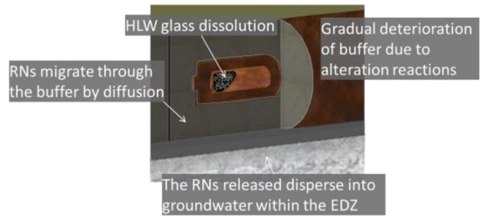
<td>
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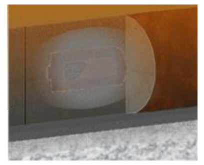
<td></td>
</tr>
<tr>
<td>・Formation of cracks in the HLW glass matrix during manufacture
・Temperature rise in the vicinity of HLW due to radiogenic heat
・Groundwater inflow from the tunnel wall
・Gaps remain between contained buffer and the overpack within the PEM handling shell
・EDZ is generated around disposal tunnels
・Oxidising conditions develop around disposal tunnels</td>
<td>・The temperature rises due to the heat generated by the HLW and eventually decreases in line with radioactivity decay
・Water penetrates the backfill
・After handling shell failure, swelling of the buffer to provide mechanical protection and prevent groundwater flow
・Gaps exist between the buffer rings and between the buffer rings and the overpack
・Gradual corrosion of the overpack and PEM handling shell consumes any remaining oxygen and environment becomes reducing
・Hydrogen gas may be produced due to corrosion of iron in the reducing environment
・Slight alteration of the buffer material by reaction with iron</td>
<td>・The temperature of the near field gradually decreases and approaches the initial rock ambient value
・The water pressure outside the EBS recovers to its pre-construction value
・The buffer swells and any gaps disappear
・The buffer and backfill are gradually altered by the reaction with groundwater
・Corrosive expansion of the overpack deforms the buffer; corrosion expansion of the PEM handling shell deforms the buffer and backfill
・Corrosion of the overpack and PEM container changes the porewater composition in the vicinity of the HLW and in the buffer
・Corrosion of the iron continues to produce of hydrogen gas.
・The overpack maintains containment for >> 1000 years</td>
<td>・The temperature and hydraulic fields are in steady state
・The groundwater flow field is affected by highly permeable structures such as altered and deteriorated concrete supports and drains left during backfilling
・HLW glass dissolution
・When the overpack is completely corroded, corrosive expansion stops
・Over time, the number of overpacks failing increases
・Hydrogen gas is produced due to both corrosion and radiolysis
・Gradual deterioration of buffer, hydraulic plugs and backfill due to alteration reactions
・RNs leached from HLW into groundwater migrate through the buffer by diffusion</td>
<td>・Changes in the temperature, hydraulic, stress and chemical fields may occur</td>
</tr>
</table>

Figure 6.3-1 Example of a storyboard: Evolution of the HLW repository in plutonic rock (PEM option)

Classification	Safety features	Components	Period			
			Period during which the current geological environment is expected to be little altered (T1 to T3)			Period during which the uncertainty regarding characteristics of the geological environment increases significantly (T4)
			Period from repository closure until complete re-saturation (T1)	Period after re-saturation until releases of RNs from the EBS (T2)	Period after RN release, when the characteristics of the geological environment are considered not to have significantly changed (T3)	
Isolation	Protection from significant effects of natural perturbing phenomena	Geological environment				
	Reduction of the likelihood of human intrusion	Geological environment				
Containment	Restriction of RN leaching (HLW repository)					
	Reduction of elution by glass matrix	Glass				
	Prevention of contact between waste and groundwater	Overpack				
	Restriction of RN leaching (TRU repository)	Waste matrix Waste packages				
	Restriction of RN migration					
	Inhibition of leaching of RNs	Geological environment				
	Reduction of RN migration due to slow groundwater flow rates	Geological environment				
	Reduction of RN migration by advection	Buffer				
	Prevention of colloid migration	Buffer				
	Sorption of RNs	Buffer				
		Infill between waste packages				
		Geological environment				
	RN dispersion	Geological environment				
	Prevention of tunnels acting as short-circuit routes for RN migration	Hydraulic plug, Backfill material				

The uncertainty of each safety function increases with the length of time it is in operation.

Figure 6.3-2 Time scales where safety functions are expected

(1) T1: period from repository closure until complete re-saturation

During construction, excavation of access tunnels/shafts and other tunnels, together with disposal tunnels/holes/vaults takes place, along with installation of all infrastructure required to ensure work safety and efficiency (ventilation, drainage, grouting/linings, etc.). Such construction, and the subsequent operational period in which waste is emplaced, will result in groundwater drainage and hydrogeological perturbations that can include lowering of the water table and local de-saturation around tunnels. Desaturation and ventilation can result in air penetration into rock walls and development of a locally oxidising environment. After HLW and TRU waste emplacement, the temperature of the EBS and surrounding host rock rises for HLW and some higher thermal output TRU waste types (Gr.2, 4HD, 4HH), although temperatures will not exceed limits set to assure that the performance of the EBS will not be significantly impacted (See Section 4.5.2 (3) (ii)).

Infilled disposal tunnels/vaults will be quality assured, so that their hydraulic conductivity is sufficiently low. Although disposal and access tunnels together with their surrounding excavation damaged zones (EDZs) are connected to each other, repository layout and installed hydraulic plugs limit the potential for short-circuit paths for groundwater (see Section 4.5.3 (3)). After closure, groundwater intrusion from surrounding rock will gradually return the repository to a fully saturated state, while any oxygen in the air introduced during construction and operation will be consumed due to reaction with EBS components or minerals in the host rock.

Groundwater and rock thus return to their original temperature and reducing conditions, in line with the decrease in thermal output of the waste as a result of radioactive decay (see Supporting Reports 4-39 to 4-41). The time required for recovery of geosphere conditions depends on the geological and hydraulic characteristics of the host rock, methods of construction and operation, and the properties of the waste. Although it will vary depending on location within a repository extending over a few km^2, recovery is estimated to take decades to hundreds of years after closure [49] [50]. However, it is understood that re-saturation time will depend on the local hydraulic conductivity and also to what extent gas is formed. In very low permeable media encountered in some other national programmes, re-saturation may take several thousand years, at least for some waste package locations. These aspects should be considered for specific sites to be explored in the future.

Where present, bentonite buffer in the EBS swells when groundwater intrudes into it and any gaps left at the time of construction seal (self-sealing), producing a very low hydraulic conductivity barrier that prevents significant advective water flow. For the specific case of H12V after the backfill is installed, groundwater flow within the disposal hole is slow during saturation, so piping erosion of buffer does not occur to a significant extent (see Section 4.5.4 (5)). At this time, minerals in the buffer and surrounding host rock keep the chemistry of the water contacting the waste package in a favourable condition for ensuring RN containment (see Supporting Report 6-15).

For TRU waste, a concrete structural framework is installed to maintain mechanical stability during the operational period. For Grs.1, 2, and 4H, this is surrounded by a bentonite buffer to strengthen the containment functions (see Section 4.4.2 (4)). Such concrete structures, together with mortar infill, or the liners and grouting around HLW disposal tunnels, will react rapidly with any inflowing groundwater to produce a hyperalkaline fluid with a local pH that could be as high as 12 to 13. At such pH, alteration of the buffer and surrounding host rock will occur, but the extent of such alteration is considered to be limited (see Supporting Report 6-8).

The HLW carbon steel overpack, which has the safety function of preventing contact between waste and groundwater for an extended period (which, at least for the SDMs considered, would certainly extend beyond the buffer re-saturation phase), will corrode gradually and uniformly while consuming residual oxygen (see Supporting Report 4-6). After porewater returns to the reducing conditions of previously undisturbed groundwater, corrosion becomes extremely slow and results in hydrogen generation (see Supporting Report 4-7). It is assumed that microbial activity in the vicinity of the overpacks and waste package containers is extremely limited, due to the low activity of water in compacted buffer, and thus their effect on corrosion is considered negligible (see Supporting Report 4-9). However, as noted in Chapter 4, there is uncertainty related to the potential for microbial activity and work on this issue is ongoing.

For the steel TRU waste package container, the high pH of the porewater (caused by reaction with cementitious material present) ensures that the corrosion rate is extremely low due to the passivation of iron; however pitting corrosion could possibly occur (see Supporting Report 4-23).

In addition to corrosion of HLW overpacks and TRU waste packages, a number of other steel containers are present in the EBS (HLW fabrication canisters, PEM handling shells for the PEM case, TRU waste conditioning canisters and drums); although these will corrode, this is not considered directly as they are not currently assigned a containment function after disposal. Nevertheless, such corrosion will contribute towards maintaining the reducing conditions of porewater.

Hydrogen generated by corrosion dissolves in groundwater or, if the production rate is greater than loss by migration in solution, formation of a gas phase will occur. H_2 will then create an overpressure, move through the EBS and disperse though repository structures and/or the surrounding rock [14] [49]. Steel, which is a constituent of many EBS components as noted above, may react with and cause deterioration of buffer and backfill, although the extent of this is considered to be negligible even for long periods (see Supporting Report 6-8). In the weaker Neogene sediments, rock creep can cause progressive deformation of the tunnel walls. This, in turn, will cause compaction of the buffer and alteration of its mechanical properties; however, it is considered that this will not compromise the designed stability of the EBS (see Section 4.4.1 (3) (iv)).

In addition, the mechanical impact on the EBS due to shaking in the event of an earthquake occurring during this period is considered minor (Supporting Report 4-17), with no effects on hydraulic conditions expected (see Section 3.4.2).

During this period, the THMC conditions in the host rock around the engineered barrier, which were disturbed by the construction and operation of the repository, will return to the original characteristics of the geological environment, so that the expected isolation and containment safety functions can be assured.

The behaviour of a repository during this period is influenced by the specification of the repository design and the processes of construction, operation and closure. For the purposes of this report, which does not cover a specific site, these issues have been considered only in very general terms. Once sites have been identified and the repository design and implementation methods have been proposed, their effects on the geological environment and the engineered barriers will be assessed by monitoring and other means, and the resultant impacts will be considered accordingly. In addition, if anomalous events such as those discussed in Chapter 5 occur before closure, the state of the repository will be set in consideration of their impacts, including those of response measures, on the geological environment after closure.

(2) T2: period after re-saturation until releases of RNs from the EBS

For HLW, as previously mentioned, corrosion progresses at a rate depending on porewater chemistry, local degree of saturation (e.g. impact of hydrogen gas phase), temperature, extent of radiolysis, etc. In the H12 report, containment by overpacks considers such factors and provides evidence that failure of containment will not occur for at least a period of 1 ky, thereby covering the time when radioactivity of the HLW is high and heat output is significant (see Supporting Reports 4-39, 4-40). In addition, the thickness of the overpack is set to ensure a large safety margin. This report also takes the 1 ky lifetime specification as a reference value for the HLW overpack but, based on more recent corrosion knowledge, for assessed SDM conditions, it is expected that the overpack containment safety function is assured for at least 17 ky after disposal (see Section 4.4.1 (2) (ix)). Furthermore, for the PEM option, it is expected that initial trapped oxygen in the repository will be consumed by corrosion of the PEM handling shell before its failure, which results in an additional extension of the overpack containment period.

For TRU waste, the containment safety function of the waste package container is not considered during design, due to uncertainties associated with pitting corrosion. Nevertheless, it can be expected that loss of containment will not occur for about several hundred years, especially for the package B design thickness of 50 mm (see Section 4.4.2 (2) (v) (b)). For waste package A, even if its integrity cannot be assured for a set time period, contact between the waste and porewater will be delayed for a certain period of time and, thereafter, restricted by the presence of the waste package components. Together with the mortar infill between waste packages, the EBS will restrict entry of groundwater. Water that gradually penetrates through the mortar infill and failed waste package containers will interact with primary waste containers, conditioning material (mortar and asphalt) and then the solid waste. For these wastes, the safety function “suppression of dissolution of radioactive substances” is considered and, even if RNs are dissolved in groundwater, their migration will be retarded by sorption onto EBS materials (significant for most RNs). Thus, the safety function of reducing releases of RNs can be assigned to the entire waste package [14], with first releases occurring only after the required time for re-saturation, which will ultimately ensure significant decay of shorter-lived RNs.

Groundwater reacts further with cementitious EBS components during this period, with further chemical changes and alteration of buffer and infill materials, plugs and backfill materials taking place. Nevertheless, the extent of alteration is limited and therefore will have no significant impact on their safety functions (see Supporting Report 6-8). As for period T1, the effects of earthquake shaking on the repository will not be significant during this period.

(3) T3: period after RN release, when the characteristics of the geological environment are considered not to have significantly changed

In this period, the conditions of the geological environment are effectively constant. Although there is the possibility that both groundwater chemistry and hydrology may be subject to short-term transients, due to tectonic processes such as earthquakes, conditions are assumed to recover quickly, thus there will be no significant effect on RN release and migration processes. However, the current assessment has not looked at the impact of climate change, with associated changes of sea-level and precipitation. This would be needed in coming assessments when potential sites are known, since the actual location of the site would determine which future impacts would be important to include here.

(a) Release and migration of RNs in the EBS and host rock

For HLW, after overpack failure, water penetrating the buffer will come into contact with the glass, which then starts to slowly dissolve. As the dissolution of glass proceeds, the dissolved silica concentration in porewater increases and the dissolution rate will gradually decrease to a long-term value (residual dissolution rate) [51] [52] [53] [54]. RNs (and other stable components) in the glass dissolve congruently with the borosilicate matrix. As the flow of water in the buffer is extremely slow, the movement of solutes from the glass surface and through any alteration layer present, occurs predominantly by diffusion. Additionally, the solution concentration of most RNs is constrained by their solubility in the porewater present. Solubilities are specified on an elemental basis: these are thus shared between the isotopes (both stable and radioactive) of the element present, depending on their specific abundance ratio [3]. RNs present in gaseous form may be entirely dissolved in groundwater due to their trace concentrations, but some may also migrate as a gas phase by mixing with hydrogen gas if this is present (see Supporting Report 6-8).

RN diffusion from the glass will be retarded by interactions with solid phases, such as sorption onto overpack corrosion products and minerals in the buffer. Migration of colloids containing RNs is prevented by the filtration function of the buffer, which effectively immobilises them [55]. During this period, radioactive decay also contributes to limit the release of RNs from the EBS. The RNs released disperse into groundwater within the EDZ and then migrate further into the surrounding undisturbed host rock (RN migration via incorporation into colloids is not considered in this study, as justified in Section 6.3.2 (3)).

Common features of the three representative host rocks are networks of fractures or other distinct water-carrying features (see Section 3.3.3 (3) (ii)), within which advective groundwater flow will occur. In general, the interior of these features is filled with various minerals generated as a result of the long-term interaction between host rock and groundwater flowing through channels or pores within them (see Section 3.3.3 (5)). Nevertheless, for the host rock as a whole, hydraulic conductivity will be low and the flow of the groundwater slow. RNs penetrating the host rock will move with the flow of groundwater, subject to mechanical advection/dispersion mechanisms and chemical interactions (e.g. sorption) with either flow path infilling minerals or the rock accessed by matrix diffusion from these paths. Thus, the movement of dissolved RNs will be slower than that of groundwater, with concentrations reduced by radioactive decay and 3D dispersion. For Neogene sediments, the hydraulic conductivity of this host rock type is relatively large compared to the other two rock types and thus significant advective groundwater flow may occur even within the bulk rock (see Section 3.3.3 (5) (b)).

For TRU waste, as described above for period T2, safety functions such as reduction of RN release are assigned to the waste matrix and waste package barriers. Such safety functions are not designed to be maintained for as long a time as the HLW EBS and thus, with time, the barrier components will degrade and RNs will be released from the EBS. At this time, as for HLW, the concentration of RNs will be constrained by elemental solubility limits within either the waste package or the infill porewater. Colloids containing RNs may be formed in the waste package, but they are not stable in porewater with high Ca concentrations that result from reaction of groundwater in the host rock with cementitious materials in the structural framework and between and within the waste packages. In porewater with high Ca concentrations, colloids are unstable and precipitate by flocculation [14] [56]. In Gr.3 and 4L waste packages and other vaults without buffer, colloids in the groundwater are not filtered by the buffer, but also flocculate and precipitate in the waste package porewater. Thus, the probability of colloidal RN migration from the waste packages is considered to be small.

In addition, although mortar waste package infill is likely to contain cracks, it has sorption functions that limit the rate of RN elution from the EBS of waste Grs.1, 3 and 4L (see Section 4.2.4 (2) (ii)). Similar functions can be expected of mortar infilled between stacked packages and structural concrete for all TRU groups. TRU waste Grs.2 and 4H have significant heat output, which could cause deterioration of EBS materials and resultant RN sorption functions. EBS materials also degrade due to reaction with groundwater and, also here, confidence in mass transfer resistance functions is gradually lost.

Organic substances contained in TRU waste decompose under the influence of radiation, heat, etc., and degradation products elute into groundwater along with RNs. Isosaccharinic acid is a typical degradation product (from cellulose under high pH conditions), which complexes strongly with some RNs, increasing their solubility and decreasing their sorption (see Supporting Report 6-17). In addition, nitrate from TRU Gr.3 eluted into groundwater can complex with some RNs, whilst increases in ionic strength may impact both the solubility and sorption of some RNs (see Supporting Reports 6-8, 6-20).

RNs released from TRU waste groups without surrounding bentonite, after interaction with EBS components, disperse into groundwater within the EDZ and then migrate further into the surrounding undisturbed host rock. During this period, radioactive decay also contributes to limit the release of RNs from the EBS. For TRU waste including a buffer, the flow of the water inside the EBS is much lower, hence both RN interactions with barrier components and radioactive decay during the longer transport to the host rock are greater, leading to significantly more attenuation of releases. In addition, for all waste groups, decomposition products could be generated from organic materials present in waste or added to ensure the workability of concrete. If so, these will impact the function of supressing RN migration in the host rock and overall geological barrier performance.

RNs released from the EBS migrate through the host rock as described above for HLW. Downstream of TRU waste vaults, however, groundwater chemistry is significantly altered by leachates from cement-based materials, nitrates from Gr.3, soluble organics, etc., resulting in alteration of minerals of the host rock/flow path and hence the safety function of retarding transport of RNs. Even in this case, TRU waste disposal will not impact the multiple barrier system of HLW, as the TRU waste emplacement area is always located at a distance on the downstream side of the total repository footprint (see Section 4.5.4 (3) (iv)). In addition, degradation products derived from organic materials left in the repository and from admixtures containing organic matter used to improve the workability of cementitious materials may also alter the performance of the host rock in controlling RN migration. Some of the RNs dissolved in groundwater may migrate in gaseous form through engineered barriers and host rocks by mixing with any hydrogen gas present (see Supporting Report 6-8).

During this period, the buffer, plug and backfill material will gradually degrade due to reactions with groundwater and hence confidence in the performance of the transport suppression safety function will also decrease. The extent of such alteration depends on the chemistry of groundwater, advective fluxes and the kinetics of the processes involved for specific materials. In the long term, alteration zones may become greater and the safety function may be degraded or lost in some cases.

(b) RN migration to the biosphere

For both HLW and TRU waste, as mentioned in Section 6.1, some long lived and mobile RNs will migrate through the host rock until they reach a pathway to the GBI. In this report, the migration model is greatly simplified and this pathway is expected to be provided by a layout determining feature (LDF - which is avoided in the layout design (see Section 4.5.1 (2))) or the repository scale model boundary. The migration distance from the near field to such a boundary is represented in the RN migration model, but the characteristics of the “short-circuits” to the GBI are not defined, with the assumption that their hydraulic conductivity is high and retardation within them would not contribute a significant barrier role. It is recognised that this may be highly conservative, as evidence of old groundwaters at depth in relevant environments suggests limited upwards flow in LDFs while their extensive alteration zones suggest a capacity for significant RN retardation. This may be assessed more realistically for specific sites.

The discharge from such a flow path to the biosphere occurs at the GBI, which is also very simplistically represented by mixing into a surface/near surface water body. This results in dilution, which is greatly dependent in the characteristics of this interface – e.g. local or regional aquifers, rivers, coastal waters, etc. [3]. Again, this is highly site-specific and will depend on hydrogeological setting, geography, topography/bathymetry, etc. and hence is represented in only a stylised manner at the present time.

(c) RN migration and exposure pathways in the biosphere

RNs that reach the biosphere will be distributed throughout the surface water circulation system, in which water movement rates are generally much faster and fluxes much higher compared to deep groundwater [3]. As a result, RN concentrations in water within the biosphere are homogenised and greatly diluted, but may be re-concentrated or captured by sorption onto soils or sediments. Human activities, such as the use of water for drinking and irrigation, plus the natural transfer of RNs through terrestrial, freshwater and marine food chains result in potential radiation exposure pathways to the population living in the release area at this future time.

(4) T4: period during which the uncertainty regarding characteristics of the geological environment increases significantly

The description of evolution of the repository above assumes careful site selection (see Sections 3.1 to 3.2), so that favourable geological conditions are maintained over a long period of time. Nevertheless, slow regional evolution due to continuous processes, such as uplift/erosion, and periodic climate change on a global scale are inevitable. Such processes can result in changes in topography, groundwater flow and chemistry, surface hydrology, etc. The specific effects will differ from place to place: for example, the effects of glaciation are limited to mountainous areas whilst, at coastal areas, the effects of uplift/erosion and sea level change may interact. As the repository is located within a deep rock formation, THMC impacts on the EBS and surrounding rock will not be significant for an long time (see Section 4.3), thus these are assumed to maintain their safety functions. However, when specific sites are assessed, long-term THMC evolution would need to be analysed to check the validity of this assumption.

On a timescale > ≈ 100 ky, however, uncertainty concerning the long-term stability of the deep geological environment will gradually increase. Additionally, although the probability of occurrence is still extremely small, major perturbations resulting from volcanism/magmatic activity and fault activity near the repository cannot be completely precluded (see Section 3.4). Furthermore, although not analysed quantitatively in this safety case, uplift and erosion may change the repository environment and could even, after a very long time, lead to exposure of repository components at the surface.

6.3.2 Developing scenarios

Based on the safety assessment procedure shown in Figure 6.2-1, together with the understanding of the behaviour as the repository after closure described in Section 6.3.1, the stepwise development of the scenarios used for safety assessment is described below.

For development of these scenarios, the specific advantages of conventional top-down and bottom-up approaches were used to formulate the adopted hybrid approach, which associates FEPs and safety functions [1], as described in Section 6.2.1. By using this hybrid approach, important scenarios directly linked to safety functions can be efficiently extracted, aiming for completeness and consistency with current scientific knowledge, based on logical screening of FEPs from the viewpoint of their relevance to these safety functions.

(1) Creation of the NUMO FEP list

In the bottom-up approach, FEPs related to the repository are extracted based on structured assessment and material from international initiatives intended to ensure relevance and completeness. In particular, the OECD/NEA has developed a general international FEP list [57] that is intended to be used without consideration of specific geological environments or waste disposal concepts (here termed i-FEPs). Following the i-FEP hierarchy and classification, a NUMO FEP list was created by adding and deleting FEPs on the basis of the boundary conditions and waste characteristics to be considered for geological disposal in Japan. Thus, the features of the geological environments shown in Chapter 3 and disposal concepts in Chapter 4 are considered, together with past studies aimed at creating Japanese FEP lists in H12 and TRU-2 [58] [59].

The NUMO FEP list includes 284 FEPs, with a structure as outlined in Figure 6.3-3 and more details given in Supporting Report 6-4. The NUMO FEP list follows the hierarchical structure of the i-FEP list. The first level represents five different areas: external factors, factors related to packaged waste, factors related to the repository, factors related to the host rock and factors related to the biosphere. Where the same process occurs in different areas of the first hierarchy, the FEPs are organised appropriately and a distinction is made by noting in brackets which area the FEP covers.

In the NUMO FEP list, FEPs are systematically selected with emphasis on completeness and hence the same process or event may be handled in multiple FEPs. For example, in the NUMO FEP list, the process “expansion of overpack caused by corrosion” is included in FEP “F2.3.4.4 corrosion”, which is the originating event, as well as in environmental features impacting corrosion: “F2.3.4.1 pH conditions”, “F2.3.4.2 Redox conditions”, “F2.3.3.2 Volume changes of materials”. In addition, the NUMO list classifies FEPs in terms of process mechanisms: these groups are thermal, hydraulic, mechanical and chemical, covering all relevant FEPs occurring within the repository system or the surrounding geosphere[5]. Furthermore, to assure the completeness of the list, FEPs describing the coupling of these processes are explicitly included as a special group (e.g., Table 1 in Supporting Report 6-4: "F2.3.1.4 The effect of thermal processes on other processes (waste package)").

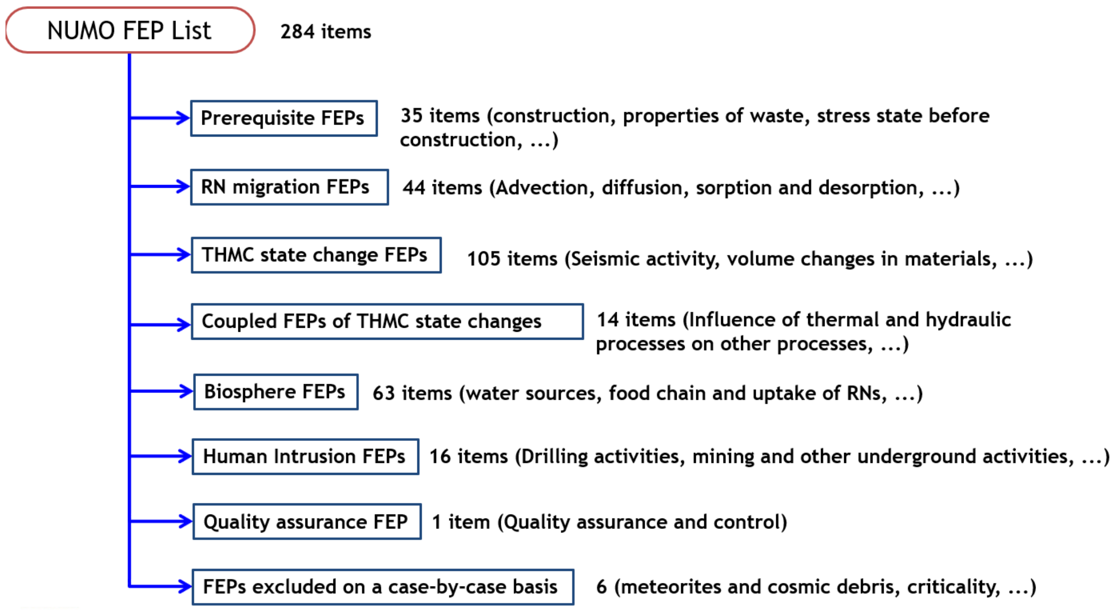


Figure 6.3-3 NUMO FEP list structure

The NUMO FEP list used in this report will be revised as necessary in the future, for example, in response to general advances in science and technology, expansion of relevant knowledge through research and development, formulation of safety regulations, and information obtained through site surveys.

(2) Development of scenarios

Using storyboards (see Figure 6.3-1) that capture system evolution after repository closure with a focus on safety functions, as described in Section 6.3.1, and taking into account uncertainties associated with such evolution, representative scenarios can be described. Using the NUMO FEP list, factors that may affect the safety function are identified in a comprehensive manner, so that the extent of such effects can be analysed.

(i) Factor analysis of safety function

(a) Extraction of state variables

As in the top-down approach, first the THMC properties that define the safety functions of each component of the target repository system are extracted and termed "state variables".

The extraction of state variables involves:

- Expanding on mechanisms defining each safety function on the basis of latest scientific knowledge.

[5] i-FEPs are classified into seven types, including THMC plus biological, radiological and gas. In the NUMO FEP list, biological and radiological are included in chemical FEPs, whilst gas is included in hydraulic or mechanical FEPs.

- In particular when quantitative models are applied to the safety function, defining the parameters included in the model and the physical and chemical variables that affect it.
- Structuring to clearly identify state variables directly affecting the safety function.

As an example, Figure 6.3-4 shows some of the extracted state variables for the safety functions of the H12V buffer, which include “inhibition of migration of RNs by advection”, “suppression of colloidal migration” and “sorption of RNs” presented in a “state variable definition diagram”.

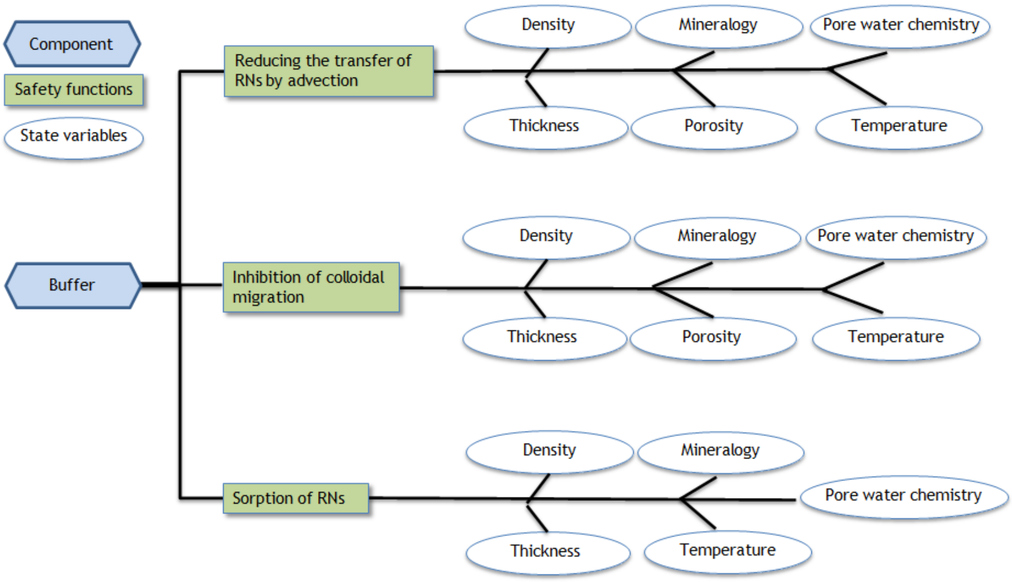


Figure 6.3-4 Example of some state variables that influence safety functions (buffer safety function)

Here, the safety function of inhibiting migration of RNs by advection requires that that the bentonite swells as it saturates, sealing fabrication gaps between buffer blocks or between the buffer and other components. However, over a long period of time, buffer may be eroded by flowing groundwater and thus its density will gradually decrease, thereby increasing the hydraulic conductivity and the possibility of advective transport of RNs. Alteration of buffer (e.g. due to interaction with overpacks or cementitious materials) may, depending on the groundwater composition, also result in hydraulic conductivity increases due to change of mineral composition, for example accompanying ion exchange in montmorillonite (conversion to Ca-type, Fe-type, etc.). In addition, there is a possibility that the hydraulic conductivity may be increased by thermal deterioration of the buffer; due directly to the increase in temperature or to associated changes in water chemistry, such as changes in ionic strength that alter the microstructure of compacted bentonite. In consideration of these aspects, “density”, “mineral composition”, “gap structure”, “thickness”, “temperature” and “porewater quality” are extracted state variables affecting the safety function of preventing advective transport through the buffer.

Supporting Report 6-6 summarises the state variables for all safety functions, organised according to the concept outlined above.

(b) Extraction of FEPs affecting state variables (use of factor analysis diagrams)

Next, the future evolution of the safety functions is analysed. Based on an understanding of the behaviour of the repository system, as described in Section 6.3.1, FEPs extracted from the NUMO FEP list are organised by a bottom-up approach, related to the state variables defining the safety functions (this is called factor analysis: see Figure 6.3-5).

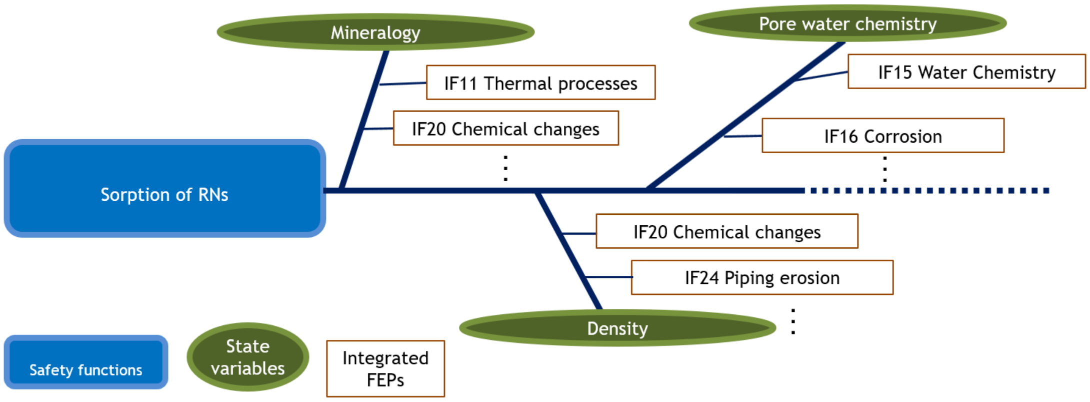


Figure 6.3-5 Example of a factor analysis diagram relating to the safety functions of the buffer (explanation of Integrated FEPs in text following)

This analysis is subject to the following constraints:

- As described in Section 2.4.4, risks due to chemical hazards are not handled in the safety evaluation of this report. Although assessments in some countries are subject to safety regulations covering such risks (for example, Sweden [60], UK [37], France [31]), these are not included in Japanese safety regulations and, for some TRU waste types, the specifications are not defined, so it would be difficult to evaluate them.
- FEPs on natural processes affecting the safety function of the repository after closure are decoupled from anthropogenic FEPs relevant to human intrusion scenarios.
- Some FEPs in the NUMO FEP list relate to actions associated with the selection of sites, design, construction, operation and decommissioning, carried out before repository closure and which define the initial status of particular safety functions. Uncertainties associated with these should be considered if they affect safety functions (for example, boundary condition FEPs or quality control FEPs, see Figure 6.3-3). With regard to such FEPs, when developing scenarios (see Section 6.3.2 (3) below), the uncertainties involved need to be considered after the factor and impact analyses described in Section 6.3.2 (2) (ii).
- FEPs which relate to migration behaviour of RNs (for example, “F2.4.1.2 dissolution” or “F2.4.1.3 diffusion”) are not taken into consideration in the factor analysis of safety functions or the impact analysis described in Section 6.3.2 (2) (ii) below. In describing the scenarios, it is necessary to include the behaviour of the RNs in a complete and consistent manner.
- Coupling between processes is not explicitly displayed in the factor analysis diagram, but, in the process of influence analysis (Section 6.3.2 (2) (ii)), such interactions are analysed along with associated uncertainties.
- In the scenarios of RN migration and resultant radiation exposure in the biosphere, at the present stage without a specific site, a generalised biosphere model based on that in the H12 report is used.

Based on the latest scientific knowledge on each FEP, this approach allows influences on state variables to be identified.

As previously noted, FEPs in the NUMO FEP list are systematically selected with emphasis on completeness, so specific processes may be handled in multiple FEPs. Therefore, the factor analysis diagram becomes complicated and it is difficult to efficiently create scenarios while keeping traceability. Therefore, after associating FEPs with each state variable, related FEPs are merged and integrated into I-FEPs in an integrated FEP list. Integration of 105 THMC FEPs resulted in 29 I-FEPs.

This simplifies the factor analysis diagram and facilitates traceability, thus enabling an efficient impact analysis to be carried out. In the Swiss safety case [51], the “OPA FEP Database” consists of 482 FEPs extracted exhaustively from the international FEP list, and “Super FEPs” (effectively integrated FEPs) consists of 38 FEPs extracted top-down based on the understanding of the disposal system. The inclusion of individual FEPs in the OPA FEP Database guarantees the comprehensiveness of the Super FEPs. This is a similar approach to that in this report, where the integrated FEP list and the NUMO FEP list are used together in order to achieve both efficiency in scenario creation and comprehensiveness of scenarios.

For the I-FEPs, it was decided to label them based on the initiating event that influences other processes. For example, expansion of overpack due to corrosion covered by “F2.3.3.2 Volume change of material (waste package)” is included within integrated FEP “IF16 corrosion”. The classification of all FEPs and the integrated FEP[6] development process are given in Supporting Report 6-5.

Figure 6.3-5 shows an example of integration of FEPs that influence “mineral composition”, “porewater quality”, and “density”, extracted as state variables for “sorption of radionuclides”, which is a safety function of the HLW buffer (see Section 6.3.2 (1)). Supporting Report 6-7 contains factor analysis diagrams for the other safety functions.

(ii) Analysis of impacts on safety functions and handling in scenarios

The starting point is provided by the I-FEPs, the state variables describing the most probable state of safety functions of the repository after closure (described in Section 6.3.1) and uncertainties in current knowledge. Scenario development then results in base scenario, variant scenario and low probability perturbation scenario. Impact analysis determines the most probable state of the safety functions and the uncertainties in the FEPs to be considered in the resultant scenario and hence its classification in terms of probability. In preparing the impact analysis table, in addition to scientific information from existing literature on phenomena related to FEPs affecting the safety function as extracted by factor analysis, additional clarification (termed “process analyses”) was performed (Table 6.3-1).

[6] For integrated FEPs, “IF” is attached to the FEP number.

Table 6.3-1 List of process analyses performed in this assessment

Analysis	Overview	SR
Buffer–overpack chemical alteration	Evaluate the effect of chemical alteration of buffer due to reaction with iron released by overpack corrosion on its safety functions.	6-8
Buffer–concrete chemical alteration	Evaluate the effect of chemical alteration of buffer due to reaction with leachate from concrete on its safety functions.	6-8
Concrete–host rock chemical alteration	Evaluate the effect of chemical alteration of host rock due to reaction with leachate from concrete on its safety functions.	6-8
Structural framework chemical alteration	Evaluate the influence of leaching of cementitious materials in the structural framework on the hydraulic conductivity of the structural framework.	6-8
Nitrate impact	Evaluate spread of, and chemical changes due to, nitrate contained in TRU waste Gr.3.	6-8
Gas migration in buffer	Evaluate effect of porewater displacement by hydrogen on the containment function and the effect of gaseous RNs on dose.	6-8
Overpack settling in buffer	Evaluate the long term (after re-saturation) mechanical stability of buffer in terms of overpack sinking due to its higher density.	4-17 4-28
Corrosion expansion	Evaluate the long term (after re-saturation) mechanical stability of buffer against additional loads accompanying overpack corrosion expansion (coupled to rock creep)	4-17 4-28
Earthquake response	Evaluate the mechanical stability of the EBS against large scale earthquake motions	4-17 4-28
Thermal impact	Evaluate the temperature rise in the buffer due to the heat generated by the waste.	4-39 4-40 4-41

Factors that are judged to have negligible influence on safety functions during impact analysis are not taken into consideration during scenario definition. Some factors that act to enhance safety functions are also clarified, but are not currently covered by the models/codes and databases used for quantitative evaluation of scenario evaluation; these are conservatively ignored. Examples here include the transport resistance of the surface-altered layer formed during dissolution of HLW glass, sorption of RNs onto iron corrosion products derived from overpacks and irreversible uptake of RNs in the buffer and host rock (mineralisation).

For HLW and TRU waste, the impact analysis tables are prepared for the components of the repository expected to have safety functions (see Table 4.2-4 and Table 4.2-5). Here, components expected to have common safety functions regardless of host rock, like buffers, are included in one table to avoid duplication. However, if there were differences identified for specific geological setting, these would be described explicitly (this is not the case for the present SDMs). As an example, the impact analysis table summarising the output of the factor analysis diagram on the safety function of the buffer (Figure 6.3-5) is presented as Table 6.3-2. The integrated FEP "IF15 water chemistry" includes "porewater chemistry", the probable state and uncertainty of which (for both HLW and TRU waste) results from reactions between groundwater and the buffer and, in particular the degree of progress of Ca ion exchange, which, in turn, impacts sorption and diffusion of RNs.

The impact analysis tables for FEPs associated with all safety functions related to HLW and TRU waste repositories, together with associated state variables, are included in

Supporting Report 6-9. In the example shown in Table 6.3-2, there are no FEPs that would be classified as variant or low probability perturbation scenario but, if such FEPs existed, they would be captured in the “Scenario classification” column. For a full description on all impacts on safety functions considered, see Supporting Report 6-9.

Table 6.3-2 Examples of impact analysis: influences of state variables describing the safety function of buffer "sorption of RNs"

Safety function/ State variable	Integrated FEP	Probable status	Uncertainty to be considered in scenario analysis	Handling classification in scenario analysis
Porewater chemistry	15. Water chemistry	• In the case of HLW, groundwater reacts with buffer to form the resultant porewater. Depending on the composition of the groundwater, alteration to Ca-type montmorillonite may occur (see Supporting Report 6-15). • Hydroxyl ions, produced by corrosion of the overpack, may increase porewater pH at the contact with the buffer, but any deterioration is limited to the vicinity of this interface (see Supporting Report 6-8). • For HLW, the influence of cementitious material on the buffer can be ignored: for hard rock the amount of concrete is limited, for weaker sediments a concrete lining would be needed, but this will not affect the buffer for the H12V case. For the PEM case, the concrete lining needs to be considered but the impact is limited since buffer alteration is suppressed (see Supporting Report 6-8).	• In alteration analysis of buffer due to corrosion of the overpack, uncertainty exists in the dissolution rate of montmorillonite, associated thermodynamic data, the secondary minerals precipitated and their effects on RN migration. • As a result of the above, there is uncertainty in both the porewater chemistry and alteration of montmorillonite, however it is considered that alteration is limited in extent (Supporting Report 6-8).	• Consider the degree of alteration and impacts on sorption and diffusion of RNs in HLW buffer. • In the base/variant scenario, changes in pH and ionic strength of buffer porewater due to corrosion of the overpack are not considered. • For HLW, it is considered that the effect on buffer due to cementitious material is negligible, this effect is not considered in the base/variant scenario.
		• For TRU waste also, groundwater reacts with buffer to form the resultant porewater (Supporting Report 6-15). At this time, high pH interactions between montmorillonite and concrete occur, but the reaction is limited to the interface of the buffer material/concrete. The assessment carried out suggests that unaltered montmorillonite predominates in the buffer, and the rise in pH is suppressed by reactions with buffer material (see Supporting Report 6-8). • Na – Ca exchange in remaining montmorillonite affects its sorption characteristics, depending on the degree of alteration (See Supporting Reports 6-8, 6-15). • For TRU waste, since no iron containers contact directly with buffer, the effect of iron corrosion is negligible.	• Uncertainty exists in the analysis of buffer alteration due to concrete associated with the dissolution rate of montmorillonite, associated thermodynamic data, the secondary minerals precipitated and their effects on RN migration. • As a result of the above, there is uncertainty in both the porewater chemistry and alteration of montmorillonite, however it is considered that alteration is limited in extent (Supporting Report 6-8).	• In consideration of sorption and diffusion of RNs in buffer, consideration is given to the degree of Ca conversion. • For TRU waste, the influence of cement interaction is limited to the interface with buffer, so it is not considered in base/variant scenario. Also, the influence of pH increase due to iron corrosion is not considered in any scenario, since the analyses of iron corrosion presented in Supporting Report 6-8 suggest the impacts on pH are too small to affect bentonite stability.
		• Effects on HLW buffer by high pH plumes derived from TRU waste are defined by the groundwater flow direction and the separation distance, allowing these to be ignored for current layouts (see Section 4.5.4).	• Since it can be avoided by design, such scenarios are not considered. It is understood that this may be more complicated to show for sites where the flow direction may change in the future,	• Influence on the HLW repository of the high pH plume from TRU waste is not considered.

Safety function/ State variable	Integrated FEP	Probable status	Uncertainty to be considered in scenario analysis	Handling classification in scenario analysis
			e.g. coastal sites in case of sea-level change.	
		• The nitrate plume due to TRU waste Gr.3 may affect the buffer porewater chemistry of other waste, depending on layout relative to the groundwater flow direction (Section 4.5.4) and the separation distance between HLW and TRU waste disposal panels.	• Since it can be avoided by design, such scenarios are not considered. It is understood that this may be more complicated to show for sites where the flow direction may change in the future, e.g. coastal sites in case of sea-level change.	• Influence of the nitrate plume on other waste is not considered.
		• In HLW and TRU waste repositories, it is assumed that no complexants are present at a level to have a significant effect on the buffer sorption characteristics, so this can be ignored. The potential of complexants from organic degradation is assessed, but judged not important.	• Since no significant source of complexants assumed to be present, this is not considered.	• In the base/variant scenario, the influence of complexants on the buffer porewater chemistry is not considered.

(3) Selection of scenarios

Here, based on storyboards (e.g. Figure 6.3-1) showing how the safety functions of the specific repository systems are expected to perform after closure of the repository, scenarios are developed in a structured manner. It is noted that there is a subjective aspect to this approach at the present time, with expert opinion playing a key role, but the aim is that the total set of scenarios would be as comprehensive as possible.

By definition, the base scenario represent the expected behaviour of specific repository systems, as illustrated in a storyboard. Based on this, the other scenarios are developed from an analysis of probability/associated uncertainties of each FEP in the impact analysis tables described in Section 6.3.2 (2). After organising the safety functions of the repository components and corresponding RN migration process for each time frame, this results in descriptions of the base, variant and low probability perturbation scenario. Transparency of the safety evaluation is ensured by considering:

- The uncertainty in the influence of FEPs on safety functions, which can have either a positive or negative impact. For discussing safety of repository options, uncertainty that has a positive influence on safety functions is conservatively ignored in the variant scenarios, which focus on uncertainties that could negatively impact safety.
- From impact analysis tables for safety functions influenced by integrated FEPs that were noted to be treated as low probability perturbations, special scenarios to consider these were developed.
- In cases where multiple uncertainties result from many related factors, uncertainty propagation is considered: where factors have very low probability it is considered reasonable to postpone detailed assessment of uncertainties until the repository system is better defined for specific sites.

In the following, base, variant and low probability perturbation scenario are described based on storyboards covering the temporal-spatial scales described in Section 6.3.1.

In describing these scenarios, regardless of the host rock, focus is on the EBS for HLW options (H12V; PEM) and options for TRU waste groups, since these have many common components and expected safety functions, which can be presented in a unified manner. In the cases where there is a difference due to the host rock, it is noted explicitly. Here, components of the repository include not only those that provide the designed safety functions, but also all others (Table 6.1-2) that could influence RN release and migration (see Section 6.3.2 (2) (ii)).

In terms of gaseous RN migration, it is considered that the inventory of sources in the waste is small (Section 6.3.1 (a)) and hence gases will dissolve in groundwater when the repository re-saturates. However, conservative dose assessment assuming that all gaseous RNs do not dissolve in groundwater and are transported to the biosphere has confirmed that the effect would be negligible (see Supporting Report 6-8). For these reasons, gaseous RN migration scenarios are not currently considered in the safety assessment.

With regard to RN migration via incorporation into colloids, organic matter and microorganisms in groundwater, there are some examples of studies [3], [14], [61], [62] that deal with such migration. However, the dose assessment results are highly dependent on the type and concentration of such colloids, organic matter and microorganisms present, and thus will be treated based on ambient geochemistry after a site has been identified.

(i) Description of base scenario

The main features of the base scenario are described below, focusing on clarification of the handling of safety functions in the RN migration analysis. This report covers the disposal of HLW and TRU waste, but elements of scenarios concerning the geology beyond the near field, the biosphere and natural perturbations are common to both.

(a) T1: period from repository closure until complete re-saturation

(A) Near field scale

- EBS

For HLW and TRU waste Grs.2 and 4H, heat generation results from decay of short-lived RNs contained therein. Locally, temperature rises in the wastes and associated buffer, but waste loading is such that buffer maximum temperature will not exceed 100 °C (see Section 4.5.2 (3) (ii)). Key buffer safety functions, Reduction of advection of RNs, Suppression of colloidal migration, and Sorption of RNs are thus not impaired as a result of any thermal deterioration. In addition, the temperature of the glass matrix is not high enough to result in thermal deterioration, and the “Low dissolution of the glass matrix” safety function is maintained. Cracks in the glass matrix that may occur during manufacture remain and are explicitly accounted for the analysis.

In the case of TRU waste Grs.2 and 4H, it is assumed that an increase in the temperature of the near field may cause alteration of concrete mineralogy, and hence it is conservatively assumed that the suppression of dissolution of RNs, function of the waste or waste package (Gr.4H), and sorption of RNs, function of waste package infill (mortar), may change.

When the repository is closed, groundwater invades slowly from the surrounding host rocks into the buffer, which was in an unsaturated state during the operational period. Groundwater saturation in the entire repository within about several hundred years after closure is assumed, although this could be longer in some cases [49] [50]. As the saturation of the buffer progresses, the thermal output of the waste decreases along with the temperature of the near field, until it approaches original rock ambient.

As the buffer for HLW and TRU Grs.1, 2 and 4H gradually saturates, it swells and generates a swelling pressure that contributes to increasing mechanical stability of the near field. This supports buffer safety functions related to restriction of the transport of RNs. In the case of the PEM option, the handling shell surrounds the buffer, but, after it loses containment, the buffer saturates resulting in similar safety functions as for the H12V case (Supporting Report 4-19).

The minerals of the host rock and buffer tend to maintain constant water chemistry (chemical buffering): oxygen introduced in air during construction and operation will be quickly consumed after closure and the porewater becomes reducing like the original, undisturbed groundwater. Residual oxygen is even more rapidly consumed by any steel repository components present (see Table 6.1-2: steel supports for disposal in Neogene sediments, rock bolts commonly used in all repositories, TRU waste packages, HLW overpacks and PEM handling shells), ensuring that porewater is reducing. As a result, this supports the safety function, suppression of dissolution of RNs.

The buffer may be partially altered (e.g., Ca–Na ion exchange) due to reaction with groundwater, but its safety functions will not be impaired by this (see Sections 4.4.1 (3), 4.4.2 (4), Supporting Reports 6-8, 6-15). In addition, due to leaching of cement-based components of the repository (see Table 6.1-2: grout material common to all repositories, shotcrete, liner and structural concrete, invert concrete, drainage infill mortar, TRU waste package infill and vault backfill), highly alkaline water is produced which can alter nearby buffer (cement-bentonite reaction), but this reaction is extremely slow and hence the extent of alteration is limited and the safety functions of the buffer are maintained (see Supporting Report 6-8). The buffer may also react with dissolved iron (iron-bentonite reaction) supplied from steel components of the repository as described above, but alteration is slow and similarly limited. Hydrogen is generated by corrosion of iron under reducing conditions, but the amount generated from rock bolts and steel rebars outside the buffer is limited: thus it is assumed that generated hydrogen dissolves in groundwater and quickly diffuses into the rock.

Gas conductivity of the saturated buffer is small and hence hydrogen generated inside the buffer (e.g., from the HLW overpack or TRU waste package) may exceed solubility in the buffer porewater and accumulate in the gas phase at interior buffer interfaces. As a result, pressure may rise until it results in breakthrough gas flow, potentially forming flow paths through the buffer. Compacted bentonite is, however, characterised by self-healing and so, any paths formed will close and the buffer will quickly recover and thereafter maintain its safety functions [14] [49] [63].

As the buffer saturates, HLW overpacks corrode. Shielding by the overpack is sufficient to suppress any oxidant formation by radiolysis of water (Section 4.4.1 (2) (iii) (c)). The corrosion rate of steel under reducing conditions is slow and thus the quality-assured overpack assures the safety function, prevention of contact between waste and groundwater, throughout this period. This assures no RN release while the buffer experiences hydraulic, chemical and thermal transients.

For TRU waste Grs.3 and 4L without buffer, chemical reductants in the host rock and steel repository components, will rapidly consume trapped oxygen during corrosion and thereafter assure reducing conditions. However, it is noted that this assumption may need further justification under high pH conditions, when corrosion is extremely low. Also, nitrate from Gr.3 may prevent the environment of this waste becoming completely reducing.

- Backfill and hydraulic plugs

At the near field scale, backfill (a mixture of bentonite and crushed rock) in disposal tunnels and other access tunnels for HLW and TRU waste, is subject to groundwater intrusion (see to Section 4.5.3 (1)). Swelling of component bentonite assures it exerts the function of prevention of access routes serving as RN pathways, although its effectiveness gradually decreases due to reaction with concrete leachate, erosion, etc. Hydraulic plugs are constructed using bentonite and thus also contribute to assuring this function, especially in terms of sealing pathways through the EDZ (see Section 4.5.3 (3)).

- Behaviour of repository components without safety functions (see Table 6.3-3)

With a direct focus on release and migration of RNs, many components of the HLW or TRU waste repository systems do not have specific safety functions. As summarised in Table 6.3-3, the behaviour of these components over this time can be described for the most probable evolution scenarios to ensure that they do not impact other EBS safety functions.

Table 6.3-3 Behaviour and uncertainty of repository components without safety features (Period covered: T1 to T4)

Components	Assumed most likely state	Condition considering uncertainty
PEM handing shell	• Corrosion and associated volume expansion are complete during time period T2. From period T3 onwards, no further alteration occurs. • The change in the stress field in the near field due to volume expansion is small and is buffered by the swelling of the buffer material (see Supporting Report 4-16). The corrosion products increase mass transfer resistance and may inhibit RN migration.	• Taking into account the uncertainty in the corrosion rate, the time for complete corrosion may be shorter. In this case, the most likely impact is an increase in mass transfer resistance, implying that uncertainty would not negatively affect the source term.
Structural framework	• As the groundwater infiltrates, the concrete component gradually dissolves from the surface inwards. By the end of period T2, the dissolution of the concrete component has progressed throughout the whole structure and is then complete. As the dissolution progresses, the hydraulic conductivity of the structure increases. • In low salinity groundwater, the internal rebars retain their passive film and so the corrosion rate is very low, so that no new cracks are formed due to corrosion expansion. • For a repository with high salinity groundwater, in Neogene and Pre-Neogene sediments, the corrosion rate of the rebars is higher and the hydraulic conductivity is increased by cracking due to corrosion expansion (see Supporting Report 6-16). Corrosion of rebars in high salinity groundwater progresses through the entire structural framework by time period T2 and no further alteration occurs from time period T3 onwards.	• Uncertainty in the rate of dissolution of the concrete components may lead to an earlier dissolution of the entire structural frame. • Uncertainty in the state of the cracks during construction may lead to higher hydraulic conductivity, even in the initial state.
Grout	• The grout dissolution progresses and is complete throughout by period T2. The dissolution of the grout is complete over the whole area by T2 and no further alteration occurs from T3 onwards. • Such dissolution increases the hydraulic conductivity of the grout-filled area.	• Uncertainty in the rate of grout dissolution may lead to an earlier loss of the concrete component.
Steel Support	• Corrosion proceeds by consuming residual oxygen, which contributes to the recovery of the groundwater to a reducing state. Thereafter, the reducing corrosion progresses slowly, and by period T2, the corrosion is complete throughout. No further alteration occurs from T3 onwards. • Referring to the results of the assessment of the effect of hydrogen gas generated by corrosion of HLW overpacks and TRU waste package containers (see Supporting Report 6-8), the generated hydrogen gas is rapidly transported into the surrounding host rock by dissolution into groundwater. In addition, volume increases due to corrosion products. • The mechanical effect of the volume increase due to corrosion products on the EBS is very small (see Supporting Report 4-28). Therefore, the effects on the field conditions for RN migration, such as increased hydraulic conductivity, are negligible.	• Uncertainty in the corrosion rate of steel supports may lead to earlier complete corrosion.

Components	Assumed most likely state	Condition considering uncertainty
Shotcrete	• By the end of the period T2, the dissolution of the cementitious components has progressed throughout and is then complete. As the dissolution progresses, the hydraulic conductivity of the structure increases.	• Uncertainty in the rate of dissolution of cementitious materials may lead to an earlier disappearance of the concrete component.
Rock bolts	• Corrosion proceeds by consuming residual oxygen, which contributes to the recovery of the groundwater to a reducing state. Thereafter, corrosion under reducing conditions progresses slowly, and by period T2, the corrosion is complete throughout. From T3 onwards, no further alteration occurs. Any hydrogen gas is dissolved in the groundwater and migrates quickly into the surrounding host rock. Even if rock bolts are completely corroded, the effect of volume expansion is limited and negligible. • The dissolution of the rock-bolt anchoring material (cementitious material) progresses, and the dissolution is completed throughout by T2. After the period T3, no further alteration occurs. The hydraulic conductivity increases with the dissolution of the concrete.	• Uncertainty in the rate of corrosion of rock bolts may lead to complete corrosion occurring earlier. • Uncertainty in the rate of dissolution of the cementitious material used to anchor the rock bolts may lead to an earlier loss of the concrete component.
Concrete liner	• By the end of the period T2, the dissolution of the concrete components has progressed throughout and is then complete. As the dissolution progresses, the hydraulic conductivity of the structure increases.	• Uncertainty in the rate of dissolution of cementitious materials may lead to an earlier disappearance of the concrete component.
Concrete invert	• By the end of the period T2, the dissolution of the concrete components has progressed throughout and is then complete. As the dissolution progresses, the hydraulic conductivity of the structure increases.	• Uncertainty in the rate of dissolution of cementitious materials may lead to an earlier disappearance of the concrete component.
Central drain	• During closure, the filling concrete is dissolved, and by the time of T2 the dissolution is complete throughout. The dissolution is completed throughout by T2, and no further alteration occurs from T3 onwards. With the dissolution of the concrete, the structure becomes highly permeable soon after backfilling.	• Uncertainty in the rate of dissolution of cementitious materials may lead to an earlier disappearance of the concrete component.
Drain pipe	• During closure, the filling concrete is dissolved, and by the time of T2 the dissolution is complete throughout. The dissolution is completed throughout by T2 and no further alteration occurs from T3 onwards. With the dissolution of the concrete, the structure becomes highly permeable soon after backfilling.	• In view of the uncertainty regarding the high quality of the concrete filling in the construction, the hydraulic conductivity of a part may be high immediately after closure.
Waterproof sheet	• The decomposition of the synthetic resin material progresses and is completed during period T2. The degradation is complete by T2 and no further alteration occurs after T3. • The main degradation products of the synthetic resin material have a low complexing ability with RNs [64].	• In view of the uncertainty regarding the rate of decomposition, the time of complete decomposition may be delayed, but the complexing capacity remains unchanged.

Components	Assumed most likely state	Condition considering uncertainty
Mechanical plug	• Corrosion of the rebar progresses and is complete throughout by period T2. After period T3, no further alteration occurs. Corrosion expansion leads to increased cracking and hydraulic conductivity of the structure. • By the end of the period T2, the dissolution of the concrete component has progressed throughout and is then complete. As the dissolution progresses, the hydraulic conductivity of the structure increases.	• Uncertainty in the corrosion rate of reinforced concrete may lead to an earlier increase in hydraulic conductivity due to cracks in the frame. • Uncertainty in the rate of dissolution of cementitious materials may lead to an earlier loss of the concrete component.
Permeable layer (crushed rock)	• After backfilling, this exists as a highly permeable structure. This condition persists throughout the entire period T1 to T4.	• —
Filter material (glass fibre)	• The dissolution of the glass fibre progresses and by period T2 is complete. After T3, no further alteration occurs. As the glass fibre dissolves, the hydraulic conductivity increases.	• Uncertainty in the dissolution rate of glass fibres may lead to an earlier disappearance.
Drainpipe	• The decomposition of the synthetic resin material progresses and is complete by period T2. No further alteration occurs from T3 onwards. • The main decomposition products of the synthetic resin have little complexing ability with RNs [64].	• Given the Uncertainty in the rate of decomposition, the time of complete decomposition may vary, but the complexing capacity remains unchanged.
Buried formwork (glass-fibre reinforced concrete)	• The dissolution of the glass fibres progresses and is complete by T2. No further alteration occurs from T3 onwards. As the glass fibres dissolve, the hydraulic conductivity increases. • The dissolution of the concrete progresses and is complete by T2. No further alteration occurs from T3 onwards. The hydraulic conductivity increases with the dissolution of the concrete.	• Uncertainty in the dissolution rate of glass fibres may lead to an earlier disappearance. • Uncertainty in the dissolution rate of concrete may lead to an earlier disappearance of concrete components.

- Host rock

During excavation of disposal holes, tunnels and vaults, an EDZ in which permeability generally increases is created in surrounding rocks, In addition, hydraulically unsaturated regions may develop during construction and operation, allowing air ingress and development of locally oxidising conditions. The HLW overpack assures the safety function prevention of contact between waste and groundwater, during this period, so the safety function of host rock suppression of migration of RNs is redundant during this period.

Also, for TRU waste, there are assessed to be effectively no RN releases over this period and the situation is the same. However, high pH leachate from concrete components will be released from the EBS, so that the surrounding host rock may be altered, but the extent of this is also assessed to be limited and the safety function, suppression of migration of RNs, will not be significantly impacted (see Supporting Report 6-8). For TRU waste Gr.3, nitrates are also eluted, which conservatively can be assumed to result in a plume of oxidising groundwater gradually developing, in which the sorption of RNs may be affected (see Supporting Reports 6-8).

(B) Panel scale

- Backfill and hydraulic plugs

At this scale, the backfilled tunnels following swelling of bentonite are designed to have hydraulic properties equivalent to those of the surrounding host rocks (see Section 4.5.3 (1)), providing the function, prevention of access routes serving as RN pathways. In addition, the installed plugs contribute to preventing any possible short-circuit flow though repository access tunnels (see Section 4.5.3 (3)).

- Host rock

An EDZ occurs in the host rock in the vicinity of excavations and permeability of these areas generally increases. As noted for the near field scale, RNs are contained in both the HLW and TRU waste EBS, which means that the safety function of suppressing RN migration is redundant. During operations, inflowing groundwater will be pumped out, potentially causing a local draw down of the water table; however, after closure, hydrogeological conditions will return to a state essentially the same as that before repository construction.

(C) Repository scale

- Backfill and hydraulic plugs

The fundamental properties of tunnel backfill and plugs at this scale are generally the same as for the above panel scale.

Exceptions relate to plugs (and other actions such as grouting) emplaced at points where tunnels penetrate major water-conducting features (layout-determining features) and to backfill and plugs in ramps and shafts that connect to the surface and hence penetrate a range of other rocks with variable mechanical, hydrogeological and chemical properties. In terms of post-closure performance, the barrier role of such components is unlikely to be significant, although this would need to be confirmed for particular sites.

- Host rock

At the repository scale, the impacts on the host rock noted at the panel scale also apply.

(D) Regional scale

- Geological environment

The geological environment gradually changes by slow processes such as uplift/erosion and glacial cycles, but safety functions such as "isolation" and "restriction of migration of RNs" and the features that determine flow paths to the GBI are maintained for very long times. For both HLW and TRU waste, no releases of radioactivity occur over this time period, so the latter function is redundant.

- Biosphere

Although the surface environment is vulnerable to changes on a shorter timescale than any other part of the system, these are inherently unpredictable so current conditions are assumed unless significant surface modification occurs (e.g. as a result of glacial cycles).

(b) T2: period after re-saturation until releases of RNs from the EBS

(A) Near field scale

- EBS

While the HLW overpack maintains the function of prevention of contact between waste and groundwater, there is no significant physical alteration of contained HLW. As complete containment can be assured for more than 1 ky after closure, relatively short-lived RNs decay (e.g. Cs-137 and Sr-90) and hence heat generation and radiation dose significantly decrease and EBS temperature becomes effectively the same as the original rock ambient.

As mentioned for period T1, PEM handling shells are not assigned a containment function and hence buffer re-saturation and overpack failure times are assumed the same for both H12V and PEM options. As corrosion progresses, the mechanical performance of the overpack gradually decreases until it eventually fails mechanically, losing the function of prevention of contact between waste and groundwater. The period until the loss of function is estimated to be about 17 ky (realistic estimation: see Section 4.4.1 (2) (ix)), even when accounting for the various uncertainties involved. It is, however, conservatively assumed that this function will be maintained for only 1 ky after closure to allow for consideration of designs with less durable overpacks. Indeed, at 1 ky after closure, containment is assumed to be lost by all overpacks although, in reality, failures would be spread over an extended period of time. This very conservative assumption will need to be re-assessed when developing site-specific overpack designs.

As discussed for T1, alteration of the buffer by dissolved iron occurs at the interface between the overpack and PEM handling shell, but its extent is limited (see Supporting Report 6-8) while hydrogen produced by this corrosion can be lost without disruption of barrier functions [49] (see Supporting Report 6-8).

For TRU waste, release of RNs into groundwater is assumed to occur after re-saturation, conservatively ignoring containment by the waste package container or primary waste containers (drums or canisters). Such releases are constrained by the functions of suppressing elution of RNs from waste or waste packages and reducing migration of RNs due to sorption in packaging or infill. Such functions gradually deteriorate due to slow leaching/alteration of concrete components of the EBS. Sorption of RNs onto the infill material is not assumed for Grs.2 and 4H, because of alteration of concrete components by heat.

Leaching of RNs from most TRU waste in contact with groundwater is assumed to occur rapidly. However, in the case of metal wastes (Gr.2 and some components of other wastes), the leaching of RNs progresses congruently with metal corrosion. The leached RNs diffuse through the waste package whilst sorbing onto the cementitious infill and waste package container. Some RNs, such as C-14, may also be released as gases, which may dissolve in groundwater or be transported with other gases (e.g., hydrogen from corrosion) [14].

RNs leached from the waste after contact with water will diffuse within the waste package and sorb onto cementitious materials infilled or around the waste package. Concrete infill gradually leaches and the solution composition in contact with it eventually evolves from Region I (pH > ≈ 13) towards Region II (pH ≈ 12.5) (see Supporting Report 6-15).

Especially in the case of TRU waste Gr.2 containing degradable organic substances, solubility of some RNs may be enhanced by complexation and sorption reduced (See Supporting Report 6-17). This may also happen for bituminised waste Gr.3, while nitrate from this waste may act as a complexant or oxidant, having similar impacts (see Supporting Reports 6-8, 6-20).

Alteration progresses at the interface between buffer and concrete, but the thickness of this layer is still limited (see Supporting Report 6-8). Conversion of buffer to Ca-type causes an increase of hydraulic conductivity and a deterioration of the swelling performance, but specifications are set so that desired functions can be assured even when this occurs (see Sections 4.4.1 (3), 4.4.2 (4)). Water chemistry resulting from reaction of buffer and concrete is buffered, maintaining RN solubility and sorption performance. For TRU waste Grs.2 and 4H, heat output gradually decreases causing temperature in the EBS to return to rock ambient (see Supporting Report 4-41).

Hydrogen gas continues to be generated due to corrosion of metals, but dissipates into the host rock without perturbing the safety functions of the buffer.

- Backfill and hydraulic plugs

Performance as during period T1.

- Behaviour of repository components without safety functions

Corrosion and alteration of the components listed in Table 6.3-3 continue as during period T1.

- Host rock

The EDZ is assumed to persist during this period, with hydrogeology and hydrochemistry elsewhere restored to original undisturbed states. While RNs are contained by the HLW overpack or within the TRU EBS, the host rock safety function of the “Restriction of RN migration” can be assured, but is redundant.

The volume of host rock influenced by the spreading high pH/nitrate plumes resulting from concrete leaching and TRU waste Gr.3 will increase, but the range of any alteration will still be limited and would not impacts its safety functions (see Supporting Report 6-8, 6-22).

(B) Panel scale

- Backfill and hydraulic plugs

The backfill and plugs will continue to degrade but their essential function of prevention of access routes serving as RN pathways will be maintained and short circuit flow via such tunnels can be precluded.

- Host rock

Over this period, the essential functions of the host rock are basically the same as for the near field scale described above.

(C) Repository scale

- Backfill and hydraulic plugs

Over this period, performance at this scale is as during T1.

- Host rock

Performance is as near field and panel scale.

(D) Regional scale

- Geological environment

As T1.

- Biosphere

As T1. Although during this period impacts due to climate change are possible (e.g. altering characteristics of GBI and surface water flows), these are irrelevant as no RN releases occur at this time.

(c) T3: period after releases of RNs occur during which the characteristics of the geological environment are considered not to have significantly changed

The period during which the characteristics of the geological environment are considered not to have significantly changed is assumed to last ≈100 ky.

(A) Near field scale

- EBS

After the HLW overpack loses the function of prevention of contact between waste and groundwater, the EBS is at rock ambient temperature and the borosilicate glass matrix begins to dissolve in water with a constant chemistry resulting from the reaction between buffer minerals, overpack corrosion products and groundwater. RNs are released congruently with the glass matrix.

Even after loss of containment, the generation of hydrogen gas continues until all steel components are completely corroded. In addition, the volume of corrosion products continues to increase, but the mechanical impact is minimised by the plasticity of the buffer. Buffer deformation due to expansion of overpack corrosion products and sinking of the dense overpack under gravity modifies the distribution of bentonite density. However, this is taken into account during design and hence there are no significant impacts on its safety functions (see Section 4.4.1 (3) (iv)).

Chemical alteration of buffer due to reactions with groundwater, iron from overpack corrosion and interactions with any concrete structures present continues, but the spatial extent of this is still limited and hence safety functions of low hydraulic conductivity, RN migration dominated by diffusion and colloidal filtration can all be assured (see Supporting Report 6-8).

Porewater in the EBS is in equilibrium (or steady state) as a result of groundwater interactions with iron corrosion products and bentonite, which buffer any impacts of water radiolysis and assure pH and redox conditions that lead to low solubility and high sorption of most RNs.

In the diffusion-dominated environment within the failed overpack, glass dissolution releases silica into solution until a limiting concentration is reached, after which point the glass dissolution rate is constant and very low (termed the residual dissolution rate) [53] [54]. Unless transport rates through the bentonite are sufficiently high, RNs released will precipitate after solubility limits are reached. Some RNs have very high solubilities (e.g. I-129, Cl-36 and Cs-135), and hence concentrations are assumed to increase until loss by diffusion matches supply from glass dissolution.

For TRU waste, after the waste package container fails, RNs are eluted from the waste matrix involved for the different groups and migrate through the EBS, with release and transport constrained by solubility limits, gradients driving advective/diffusive flow and associated material permeability/diffusivity and retardation processes (generally covered by sorption).

Colloids containing RNs may be formed in the waste package, but they are not stable in porewater with high ionic strength (Ca concentrations) that result from reaction of groundwater in the host rock with cementitious materials in the structural framework and between and within the waste packages. In porewater with high ionic strength, colloids are unstable and precipitate by flocculation [14] [56]. Therefore, RNs are assumed to migrate as solutes without forming, and/or sorbing onto, colloids.

In the current assessment, release constraints set by slow waste matrix degradation is conservatively ignored and instant releases are assumed, apart from the metallic waste in Gr.2. In a more detailed, less conservative, assessment such release processes should be described in detail and associated uncertainties assessed.

Cementitious components in TRU waste packages and other wastes, as well as in the infill material, are further dissolved, with dissolved RN migration constrained by sorption reactions on solids present. In the case of high heat wastes Gr.2 and 4H, no sorption function is assumed due to possible thermal degradation of the infill material. As previously noted, in the case of TRU waste Gr.2, solubility of some RNs may be enhanced by organic complexation and sorption reduced (See Supporting Report 6-17) while nitrate from waste Gr.3 may act as a complexant or oxidant, having similar impacts (see Supporting Reports 6-8, 6-20).

TRU waste Grs.1, 2 and 4H include a buffer, which will continue to interact with cementitious material over this time, but the extent of alteration is limited and key safety functions (preventing advection, filtering colloids, buffering water chemistry, limiting RN solubility, RN sorption) are assumed to be maintained (see Supporting Report 6-8) for the entire period.

The corrosion of metals (metals in the waste, waste packages, reinforcing bars (rebars) in the structural framework) and the radiolysis of water in a reducing environment will continue to produce hydrogen gas, but if it migrates through the buffer either as a solute in porewater or in the gas phase, it will dissolve and dissipate quickly in the groundwater in the host rock, thus maintaining the safety function of the buffer [14].

- Backfill and hydraulic plugs

The backfill and plugs will continue to degrade but their essential function of prevention of access routes serving as RN pathways will be maintained during this period and short circuit flow via such tunnels is assumed to be precluded.

- Behaviour of repository components without safety functions

Corrosion and alteration of the components listed in Table 6.3-3 continue until complete degradation occurs.

- Host rock

Conservatively, the EDZ is assumed to persist, although some self-healing may occur in softer rocks. Over this period the host rock generally maintains its original mechanical, hydrological and chemical properties: changes may occur over this time due to processes like glacial cycles, especially in coastal locations, but these are very site-specific and not considered at the present time. For both HLW and TRU waste, the safety function of host rock restricting releases of radioactive substances, applies for any RNs released from the EBS. RN transport through the host rock in plutonic rocks and Pre-Neogene sediments predominantly occurs in a fracture network, with advection/dispersion in the fractures and matrix diffusion into, and sorption onto the minerals within, the surrounding rock (see Sections 3.3.3 (5) (a) and (c)). Transport through, and reactions with, fracture infill are conservatively neglected at present. In the Neogene sediments, in addition to advection in fracture networks, RN transport by advection/dispersion may occur in the rock matrix, associated with sorption onto minerals contacted (see Section 3.3.3 (5) (b)). Since bentonite colloids are considered unlikely to occur in the model groundwater in this report (see Supporting Report 6-9), RNs transferred to the host rock will migrate as solutes without sorption to colloids.

The volume of host rock influenced by the spreading high pH/nitrate plumes resulting from concrete leaching and TRU waste Gr.3 will increase, but it is currently assumed that, for at least some of the flow path, the host rock RN migration limitation function is maintained for this period (see Supporting Report 6-8) although sorption of RNs will be affected within these plumes (see Supporting Reports 6-8, 6-22). It is not expected that the organic material in some of the TRU wastes will result in a significant organic plume in the host rock.

(B) Panel scale

- Backfill and hydraulic plugs

As for near field scale.

- Host rock

As for near field scale.

(C) Repository scale

- Backfill and hydraulic plugs

As for near field and panel scales.

- Host rock

Constant hydrogeological rock properties at this scale are presently assumed, as for the near field and panel scales. Over this time period, for the sites considered, RNs gradually migrate along the groundwater flow paths defined by rock structures and hydrogeological boundary conditions that are effectively constant, whilst sorbing onto the minerals contacted. In principle, the flow path length is defined by regional hydrogeology, but assessment considers short-circuits to the GBI through major faults or undefined features at the downstream boundary of the repository scale model.

As at smaller scales, the portion of host rock influenced by the spreading high pH/nitrate plumes resulting from concrete leaching and TRU waste Gr.3 will increase, but its range will be limited by mass-balance constraints and it is presently assumed that the host rock RN migration limitation function is maintained to some extent, but with increasing uncertainties (see Supporting Reports 6-8, 6-22).

(D) Regional scale

- Geological environment

The geological environment continues to change gradually due to uplift, subsidence, erosion and climate/sea level change, with the thickness of overburden above the host rock generally decreasing along with depth below surface, but the safety functions “isolation” and “restriction of migration of RNs” are assumed to be maintained over this period (Supporting Reports 3-36, 6-10). RNs released from the host rock are assumed to travel through short circuits to the GBI provided by major water-carrying features, being retarded by sorption on infilling minerals.

- Biosphere

During this period, RNs will reach the GBI and then potentially impact populations living in the surrounding area at that time. Before and during the time of RN release, it is likely that the GBI will change, along with both surface hydrology and human lifestyles. As such changes are inherently unpredictable, distribution of RNs through the surface environment and food chains and resultant radiation exposures utilise stylised biosphere models based on biosphere characteristics and human lifestyles typical of Japan at the present time.

(d) T4: period during which the uncertainty in characteristics of the geological environment increases with time

In general, the geological environment of well selected sites is considered to be stable for at least ≈100 ky, this being the period covered by T3 above. However, as time increases, so does the likelihood that geological environment changes will significantly affect the safety functions of the repository.

Uplift and erosion are key natural perturbations that may have a significant influence on the likely evolution of a Japanese repository. This report assumes that a site with a high probability of being suitable is selected (see Section 1.4.1). Even with this assumption, it is not possible to constrain impacts on RN release and migration behaviour on timescales in the order of 1 My at repository design depths (Section 4.3); although overburden decreases, its impact is constrained by uncertainties related to uplift/erosion rates. Thus, in the current assessment, it is simply assumed that there will be no decrease in depth or associated THMC state changes (see Supporting Report 6-10). However, it is emphasised that models covering such time periods are used to illustrate general trends and output is not to be considered as fully quantitative. Nevertheless, more realistic assessments of at least some of the time period beyond 100 ky may be possible for specific sites.

(ii) Description of variant scenario

As described in Section 6.1.5 (2), the variant scenario capture uncertainties in the understanding and conceptualisation of the evolution of the repository not captured in the base scenario, with a focus on impacts on safety functions. For the base scenario described above (see Section 6.3.2 (3) (i)), uncertainties in each component of the repository impacting safety functions are extracted by impact analysis (see Supporting Report 6-9) and the following variant scenario were developed.

(a) Variant scenario for HLW

Scenario in which the rate of glass dissolution could be greater than the base scenario were considered, taking into account the uncertainty due to the following factors influencing glass dissolution.

Changes in the extent of cracking due to overpack corrosion expansion

Although the manufacture of HLW is carried out under strict quality control, cracks do occur during cooling. After the HLW is encapsulated in an overpack and disposed of in the repository, the stress field changes due to swelling of the buffer during re-saturation and volume expansion caused by corrosion of the overpack, but this does not affect the initial extent of cracking described above (base scenario). However, knowledge of changes in applied stress and consequent changes in fracturing after disposal is limited and uncertain, so this is treated in the variant scenario.

Concentration of dissolved silicate in groundwater in contact with HLW

Following overpack corrosion and loss of its integrity, the glass comes into contact with buffer porewater and begins to dissolve, resulting in a high concentration of dissolved silicate (base scenario). The concentration of dissolved silicate in the solution in contact with glass is uncertain, as it may decrease due to either sorption onto the corroded overpack or buffer or co-precipitation. These are taken into account in the variant scenario, as uncertainties associated with the concentration of dissolved silicate have a significant effect on glass dissolution rate.

(b) Variant scenarios for metal wastes

RNs contained in Gr.2 wastes are leached into groundwater due to congruent corrosion of metals such as zircaloy (base scenario). The corrosion rate of zircaloy is affected by both the temperature and extent of hydride formation. Considering the uncertainty of this corrosion rate due to the temporal variation of repository conditions, this is developed as a variant scenario.

(c) Variant scenarios covering uncertainty in spread of the nitrate plume

A variant scenario covers uncertainty in the spread of the nitrate plume from Gr.3 waste into downstream host rock, which would affect the containment safety function of the host rock. The base scenario assumes this occurs, but only to a limited extent (base scenario). However, the extent of spread of nitrate from each waste package is uncertain because it depends on the distribution of hydrological and chemical conditions on a repository scale and timing of water contact within each waste package. In view of this uncertainty, the variant scenario assumes a wider plume spread than the base scenario.

(d) Variant scenarios for temperature effects on solubility

The solubility of RNs is affected by temperature, which is assumed to decrease to that of the ambient host rock temperature by the time the RNs are leached from higher heat emitting waste, and it is assumed there is no significant temperature dependence of solubility between room temperature and rock temperature (base scenario). However, the temperature dependence of solubility is uncertain and would need to be revisited in future safety assessments. The timing of the onset of RN leaching is particularly uncertain for TRU wastes, as it depends on the corrosion of the waste package container and the leaching behaviour of the cementitious material in the waste package. Due to these uncertainties, the leaching of RNs may start when the temperature in the repository is higher than rock ambient. Uncertainties in temperature that increase solubility are treated as variant scenarios.

For the repository components that have not been given a safety function, Table 6.3-3 shows that the most plausible state, described in the base scenario, is that reaction with groundwater will progress further with time from the state assumed in T1 to the state assumed in T2 and continues after T3. In the variant scenarios, the most plausible states of the alteration process are treated by setting up states that take into account associated uncertainties, which are also shown in Table 6.3-3.

(iii) Description of low probability perturbation scenarios

Low probability perturbation scenarios are defined to cover the inherent uncertainty that remains in descriptions of very long timescale evolution, even if site selection and facility design are appropriately carried out. Despite the probability of occurrence of major perturbations being very low over the time periods considered in Sections 6.3.2 (3) (i) and 6.3.2 (3) (ii), the repository system aims to be sufficiently robust that, even if these were to occur, there is no major radiological impact (see Section 6.1.5 (2)).

Volcanic/magmatic activities and active fault movement are important perturbing natural events in Japan which, although they have a very small probability of occurrence for relevant geological environments (Supporting Report 6-9), may have a significant impact on the repository.

As described in Section 3.4.1, in the forearc region of Tohoku and Shikoku, volcanic/magmatic activity is not credible (negligibly low probability) over the next 1 My or so. However, in other areas, this cannot be assured for times greater than ≈100 ky. Thus, after 100 ky, such activity is assumed to occur, resulting in a “new volcano scenario”.

In terms of major fault movement directly perturbing a deep repository, as shown in Section 3.4.2 and discussed in Supporting Report 3-35, it is unlikely that relatively small-scale faults at a repository scale could develop into much larger active faults over relevant timescales. Nevertheless, this assumption is the basis of the developed “fault perturbation scenario”. Here, the probability that a fault may directly impact the repository was calculated to be in the order of 10^{-7}/y (see Supporting Report 3-35).

In this report, the safety of repositories located within the three representative SDMs is discussed without considering regional aspects. At present, therefore, the probability of occurrence of these such scenarios is taken to be the same for the three host rocks.

With regard to very unlikely natural perturbations (see Table 3.1-3), calculations of doses involve quantitative evaluations based on data that is currently very uncertain. After sites are specified, however, better founded evaluations will be made based on the more detailed information obtained through site investigations.

6.3.3 Setting analysis cases

Based on the scenario descriptions, analysis cases are set in order to quantitatively evaluate their radiological impacts. In setting these cases, the required models and datasets are summarised, and then used for the RN migration analyses and associated dose evaluations. It should also be noted that the migration calculations extend until 10 My, i.e., much beyond the time when repository and site evolution can be predicted. In this report, with the aim of comparing the behaviour of repositories for specific SDMs to the generic H12 and TRU-2 assessments, it was decided to continue the evaluation to determine the time of appearance of the maximum dose (see Section 6.1.4).

The base case, which are the analysis case corresponding to the base scenario, are set according to the most reasonable assessment of safety functions and their evolution in time. For the variant analysis cases, corresponding to specific variant scenarios, the influence of different models and data that capture scenario uncertainties are investigated, whilst maintaining links to the base case migration models and datasets. As described in Section 6.1.5 (2), alternative evaluation models and data sets are also presented, considering uncertainties in the base case models and data.

For low probability perturbations scenarios, analysis cases (hereinafter referred to as “low probability perturbation cases”) are set by establishing appropriate models and data for each of the selected scenarios.

The analysis cases corresponding to each of these classes of scenario are described below, with more details provided in Supporting Report 6-11.

(1) Setting analysis cases for base scenario

As noted above, there is no major difference in the description of the base scenario for the H12V and PEM options. It is understood that this is a great simplification, e.g., evolution of the system when the PEM shell ruptures and how this affects the buffer and surrounding backfill could affect near field migration. However the simplified model used in this assessment does not consider such impacts. Nevertheless, it is clear that the definition of base scenario will need to be revisited for future, more realistic analyses.

As the goal is RN release and migration analysis, the HLW base scenario focus on time period T3 (see Section 6.3.2 (3) (i) (c), Table 6.3-4 and Table 6.3-5). Table 6.3-4 summarises the migration behaviour of RNs in the base scenario and the way of handling this in the associated quantitative analysis. Table 6.3-5 shows the most probable state assumed for components of the repository listed in Table 6.3-4 and the impact analysis table for safety functions (Supporting Report 6-9). The “most probable states” for the components of the repository that have not been assigned safety features are shown in Table 6.3-3 and, for each of these components, treatment in the RN migration analysis is described. As described in the base scenario, no RN migration occurs up to period T2, but the change in repository conditions prior to period T3, are captured in their specification when RN migration starts. In period T4, the repository behaves in the same way as in T3.

The process is similar for TRU waste, which also focuses on time period T3 (see 6.3.2 (3) (i) (c)) while Table 6.3-6 and Table 6.3-7 summarise the handling of RN migration analyses and the state of each component, respectively.

Based on the concepts presented here, the background is set for the RN migration models and datasets described in Section 6.4.1.

Table 6.3-4 RN release and transport for HLW base scenario (T3: period after releases of RNs occurs during which the characteristics of the geological environment are considered not to have significantly changed)

Description of RN migration behaviour in base scenario	Concept of handling in RN migration analysis
• Congruent release of RNs with glass dissolution.	• Representation of RN leaching by constant rate. • Set the release rate according to the dissolution rate of glass.
• The concentration of the RNs in the groundwater on the inner side of the buffer is limited by solubility; precipitated RNs will remain on the inner side of the buffer (between overpack and buffer). • There is the possibility that the formation of colloids on the inner side of the buffer will result in the uptake of RNs, but because of the colloidal filtration function of the buffer, colloidal RN transport will be inhibited.	• Consider dissolution and precipitation of RNs in the region on the inner side of the buffer, assuming thermodynamic equilibrium and redox buffering by iron corrosion products. • Consider migration only of RNs dissolved in porewater.
• RNs dissolved in the porewater migrate through the buffer material by diffusion while sorbing onto minerals, being released to the EDZ. • Since bentonite colloids are unlikely to be generated in the model groundwater set up in this report, RNs migrate to the host rock as solutes without sorption to bentonite colloids.	• Volume between glass matrix and buffer modelled as a mixing tank. • Consider RN migration by Fickian diffusion with linear sorption in buffer and empirical correction for charged microporous structure. • Outer boundary modelled as mixing tank in EDZ. • Sorption by glass alteration products, overpack corrosion products, and also transfer path restriction in fractured glass/overpack is ignored.
• RNs in the EDZ are transferred through the host rock by slow groundwater flow through the matrix and/or structural discontinuities, with diffusion into connected non-flowing porosity and sorption onto mineral surfaces contacted.	• The EDZ is treated as a porous media and the RNs mix instantaneously with groundwater. • Consider migration by advection on the downstream side of EDZ. • Simplify fractures or other discontinuities in which advective flow occurs and model with parallel plates. • Consider diffusion from fracture into rock matrix and sorption to mineral surfaces. • Sorption on the fracture surface is conservatively not taken into consideration.
• Randomly distributed fractures form heterogeneous 3D network, in which RN migration takes place.	• Express the characteristics of RN migration in a 3D heterogeneous medium with one-dimensional model.
• Radioactive decay during transition.	• Consider RN decay and ingrowth.
• After reaching a major fault, RNs migrate through it and reaches the biosphere.	• Set up a pathway in which RNs migrate through host rocks to major faults and then to GBI.

Table 6.3-5 Analysis of components within the HLW base scenario (T3: period after release of RNs occur during which the characteristics of the geological environment are considered not to have significantly changed) (1/2)

Component	Safety function	Assumed state	Concept of handling in RN migration analysis
Glass	Reduction of elution by glass matrix	• Groundwater contacts the vitrified waste and the glass dissolves. • Dissolution of the glass decreases with the resulting increase of the dissolved silicate concentration and then reaches a constant long-term dissolution rate. • There is no significant impact on the concentration of dissolved silicate due to reactions involving iron corrosion products and/or buffer. • There is no noticeable modification of cracks caused during glass production. • The temperature at the time of glass dissolution is ambient rock temperature and does not change. • The concentration of RNs is limited by their solubility in porewater resulting from reaction of groundwater, buffer and iron corrosion products of the overpack. RNs that exceed the solubility limit precipitate.	• Since the uncertainty of the time required for re-saturation is large, this time is not set and it is assumed re-saturation is complete immediately after closing. Re-saturation would, in any case, be complete at the time when the overpack fails. • Apply a glass dissolution model using the long-term dissolution rate. • Set the glass dissolution rate in consideration of the increase in surface area due to cracks during fabrication.
Overpack	Prevention of contact between waste and groundwater	• The earliest loss of safety functions after 1 ky. • Volume expansion due to iron corrosion products continues. • As the fabrication canisters are not expected to prevent contact with groundwater, water will immediately come into contact with the glass after the overpack loses its safety function.	• In the analysis model, failure assumed after 1 ky. • Overpacks and canisters are not considered in the analysis of RN migration.
Buffer	Prevention of RN migration by advection	• Alteration of buffer due to corrosion of overpacks (and PEM handling shells, if present) is restricted to the interface and, since most parts are sound, low hydraulic conductivity is assured and RN migration is dominated by diffusion, so the safety function is maintained. • The buffer deforms due to corrosive expansion of overpack and overpack sinking; the distribution of bentonite density changes, but the safety function is maintained by the design specifications.	• Only solute transport by diffusion is handled.
	Prevention of colloid migration	• Because deterioration of buffer due to overpack corrosion is limited to the interface and, since most part is sound, colloid filtration function is maintained. • The buffer deforms due to corrosive expansion of overpack and overpack sinking; the distribution of bentonite density changes, but the safety function is maintained by the design specifications.	• Do not consider colloidal migration through the buffer.
	RN sorption	• The buffer porewater is assumed to be in equilibrium with the bentonite, defining its sorption properties. • Depending on groundwater chemistry, ion exchange of montmorillonite occurs and the sorption properties change.	• Consider alteration of bentonite from Na-type to Ca-type according to the groundwater chemistry when setting the RN sorption parameters (see Supporting Report 6-15).

Component	Safety function	Assumed state	Concept of handling in RN migration analysis
			• Consider changes in the ionic strength of the buffer porewater due to reaction with groundwater when setting the RN sorption parameters.
Geological environment	Protection from significant impacts of natural perturbations	• Site selection will exclude areas where such risk is significant.	• By definition not considered in these scenario.
	Reduction of RN dissolution	• Due to the reaction between buffer and groundwater, the composition of buffer porewater changes with time. • The concentrations of RNs in porewater are limited according to their solubility, set for porewater chemistry with redox set by iron corrosion products; RNs exceeding the solubility limits precipitate. • The near field temperature is host rock ambient and the solubility limits are defined for this.	• Set solubility in consideration of temporal and spatial variability of buffer porewater. • Consider migration only of RNs dissolved in buffer porewater.
	RN sorption	• The influence of the alkaline and nitrate plumes originating from Gr.3 concrete is limited to the vicinity of the tunnel and sorption performance is maintained in other areas. • RNs may react with any surfaces encountered, which can generally be represented as reversible, concentration-independent sorption, although effectively irreversible mineralisation may also occur.	• Do not consider the effect of high pH in setting the RN migration parameters of host rock, since only a very short part of the migration path would be affected. • Model sorption with Kd. • The RN migration analysis is performed assuming that the safety function operates only in the host rock area downstream of the tunnel at the end of a HLW disposal or of the TRU repository.
	RN dispersion	• RNs are dispersed by a network of fractures of different sizes, orientations and hydraulic properties.	• Model the flow and migration in multiple realisations of stochastically generated Discrete Fracture Networks (DFNs). • The average transport characteristics were set based on the statistically generated DFN.
	Retardation of RN migration due to slow groundwater flow velocity	• A slow groundwater flow field is maintained. • Slow advective flow occurs through the matrix and/or structural discontinuities. • An EDZ is generated near tunnels and hydraulic conductivity in this region increases.	• Apply a stable hydraulic gradient and hydraulic conductivity during the evaluation period. • Consider the influence of discontinuities on the flow of groundwater. • Set the EDZ width and hydraulic conductivity.

Component	Safety function	Assumed state	Concept of handling in RN migration analysis
		• The EDZ is mechanically stable over this time and remains highly permeable, although it is subject to stresses on the rock mass due to swelling of the buffer and corrosive expansion of the iron-based components [65].	• For RN-transport, the EDZ is conservatively modelled as a mixing tank.
Hydraulic plug, Backfill material	Prevention of tunnels acting as short-circuit routes for RN migration	• Swelling backfill material seals and gaps between it and the tunnel wall. • When concrete is present, the backfilling material deteriorates due to high pH leachate and hydraulic conductivity increases. • Alteration of the hydraulic plug is limited and the desired performance is maintained.	• The backfill hydraulic conductivity is set considering the extent of alteration, depending on the amount of concrete used. • The hydraulic plug is treated assuming its designed function is assured.

Table 6.3-5 Analysis of components within the HLW base scenario (T3: period after releases of RNs occur during which the characteristics of the geological environment are considered not to have significantly changed) (2/2)

Component	Safety function	Assumed most likely state	Concept of handling in RN migration analysis
PEM handling shell	-	• Corrosion and accompanying volume expansion occur. The change in the stress field of the near field due to volume expansion is small and is buffered by the plasticity of the buffer (see Supporting Report 4-16). • Mass transfer resistance (of solute/gas) increases due to corrosion products and there is possibility of these suppressing migration of RNs.	• Is not considered in the analysis model.
Grout	-	• Leaching of grout proceeds, possibly increasing hydraulic conductivity locally.	• Considering the uncertainty in the leaching rate, assume complete degradation and ignore any effect of reduced hydraulic conductivity of EDZ due to grout.
Steel support	-	• Corrosion under reducing conditions is slow and generated hydrogen gas is assumed to dissolve in groundwater and migrate into the surrounding host rock. • Mechanically stable, with compaction of the backfill due to volumetric expansion of the corrosion products.	• Alteration is limited and, since the altered part does not become a continuous structure, it is not included in the model.
Shotcrete	-	• Complete leaching of the cementitious material and localised hydraulic conductivity increase.	• Considering the uncertainty of rate of alteration, in the 3D groundwater flow analysis model, assume complete degradation at the time of first RN release.
Concrete liner	-		
Concrete invert	-		
Rock bolts	-	• Eventually the rock bolts will completely corrode, fixing material will completely leach and hydraulic conductivity will increase.	• Although the hydraulic conductivity increases, since it does not have a continuous structure, the influence on the groundwater flow field is small and is not incorporated into the model.
Central drain	-	• Leaching of concrete infill progresses until closure. • After backfilling, it exists as higher hydraulic conductivity feature.	• Because it is a local structure, the influence on the groundwater flow field is considered to be limited, and therefore is not incorporated into the model. • Since the decomposition products of the drain pipe are distant from the RN source, treat as having no influence on the barrier performance.

Component	Safety function	Assumed most likely state	Concept of handling in RN migration analysis
Waterproof sheet	-	• Complete decomposition of the synthetic resin. • The expected decomposition products of the synthetic resin waterproof sheet have little complexation with RNs, so their influence is negligible [64]. However, the potential impact of such degradation would need re-assessment when materials are selected in future designs.	• Since the decomposition products of the waterproof sheet are distant from the RN source, treat as having no influence on the barrier performance.
Mechanical plug	-	• Corrosion expansion of rebars increases cracks in concrete and increases hydraulic conductivity. • Complete leaching of the cementitious material and localised hydraulic conductivity increase.	• Because it is a local structure, the influence on the groundwater flow field is considered to be limited, and therefore is not incorporated into the model.
Permeable layer (crushed rock)	-	• After backfilling, it exists as a highly permeable feature.	• Because it is a local structure, the influence on the groundwater flow field is considered to be limited, and therefore is not incorporated into the model.
Filter material (glass fibre)	-	• Complete dissolution of the glass fibre.	• Because it is a local structure, the influence on the groundwater flow field is considered to be limited, and therefore is not incorporated into the model.
Drainpipe	-	• Complete decomposition of synthetic resin. • The expected decomposition products of the synthetic resin drain pipe have little complexation with RNs, so their influence is negligible [64]. However, the potential impact of such degradation would need re-assessment when materials are selected in future designs	• Consider hydraulic conductivity equivalent to sand.
Buried formwork (glass fibre reinforced concrete)	-	• Complete dissolution of the glass fibre. • Leaching of concrete progresses, and any concrete component disappears.	• Because it is a local structure, the influence on the groundwater flow field is considered to be limited, and therefore is not incorporated into the model.

Table 6.3-6 RN release and transport for TRU waste base scenario (T3: period after releases of RNs occur during which the characteristics of the geological environment are considered not to have significantly changed)

Description of RN migration behaviour in the base scenario	Concept of handling in RN migration analysis
• RNs are eluted from TRU waste and concentration gradients drive releases from the waste package. • For metal waste contained in Gr.2, RNs contained in the metal leach into porewater as a result of corrosion. • The groundwater in the host rock entering the waste package has reacted with the cementitious and iron-based components and, in Grs.1, 2 and 4H, with the buffer material installed.	• For most TRU waste, elution of RNs into the EBS porewater is treated as being instantaneous after contact with porewater, with the entire EBS is treated as a mixing tank. • An exception is the metal waste in Gr.2, RNs are handled as being eluted congruently with the corrosion of the metal, specified by a constant corrosion rate, and then, as described above, instantly mixed in porewater. • The concentration of RNs is limited by solubility in the porewater within and around waste packages, set by reactions with cementitious material, iron corrosion products and buffer (Grs.1, 2, 4H).
• Some RNs sorb to the cement components of the waste package infill. • Solute migration through the EBS by advection (Grs.3, 4L) or diffusion (Grs.1, 2, 4H).	• Consider sorption on waste package infill. • However, in the infill between waste packages in Grs.2 and 4H, there is uncertainty in the sorption by cement hydrates that have been altered by higher temperature, so such sorption is conservatively excluded from the model. • RNs eluted from TRU waste are mixed instantaneously with the porewater within the structural framework.
• The concentrations of RNs in the porewater within and around waste packages are limited by the solubility, and those exceeding solubility limits precipitate. • Colloids are assumed unstable in the high ionic strength of the porewater.	• Consider dissolution and precipitation of RNs in waste packages, assuming thermodynamic equilibrium. • Consider migration of RNs dissolved in porewater.
• RNs dissolved in porewater migrate by diffusion, while being sorbed by minerals in the buffer (Grs.1, 2, 4H).	• Consider sorption of the RNs in the buffer. • In the buffer, only migration by diffusion is considered. • Outer boundary is defined as a mixing tank in the EDZ (see Supporting Report 6-13).
• RNs reaching the EDZ are transferred through the host rock by slow groundwater flow through the matrix and/or structural discontinuities, with diffusion into connected non-flowing porosity and sorption onto mineral surfaces contacted. • Bentonite colloids are assumed unstable in the model groundwater and only RNs dissolved in groundwater migrate.	• Consider migration by advection on the downstream side of EDZ. • Simplify fractures or other discontinuities in which advective flow occurs and model with parallel plates. • Consider diffusion from fracture into rock matrix and sorption to mineral surfaces. • Sorption on the fracture surface is conservatively not taken into consideration.
• Randomly distributed fractures form a heterogeneous 3D network, in which RN migration takes place.	• Express the characteristics of RN migration in a 3D heterogeneous medium with a one-dimensional model.
• Radioactive decay during transition.	• Consider RN decay and ingrowth.
• After reaching a major fault, RNs migrate through it to the biosphere.	• Set up a pathway in which RNs migrate through host rocks to major faults and then to GBI.

Table 6.3-7 Analysis of components within the TRU waste base scenario (T3: period after releases of RNs occur during which the characteristics of the geological environment are considered not to have significantly changed) (1/2)

Components	Safety function	Assumed most likely state	Concept of handling in RN migration analysis
Waste package	Reduction of RN elution	• The waste package container fails (in the case of waste package B). • Water penetrates into the waste package and RNs are eluted from the waste. • For metal waste contained in Gr.2, RNs contained in the metal leach into porewater as a result of corrosion. • The mortar component of infill gradually degrades. • The composition of the solution in contact with the mortar within the waste package evolves from defined Region I to Region II. • The concentrations of RNs in porewater are limited according to their solubility, set for porewater chemistry by cementitious materials and buffer; RNs exceeding the solubility limits are precipitated. • The near field temperature is host rock ambient and the solubility limits are defined.	• Since the uncertainty of the time required for re-saturation is large, this time is not set and complete re-saturation is assumed immediately after closure. • Although the waste package is expected to be resistant to mass transfer during the period, when unaltered parts of these remain, this resistance is disregarded in the RN migration analysis because of the large uncertainty about the duration of this state of the package. • Elution of RNs begins immediately after groundwater comes in contact with waste. • For the metal waste in Gr.2, RNs are handled as being eluted congruently with the corrosion of the metal, specified by a constant corrosion rate. • Assumed the buffer and groundwater are in equilibrium instantly, and consider the change of porewater chemistry with time and spatial heterogeneity in response to groundwater intrusion (Grs.1, 2 and 4H). • Porewater chemistry is further changed by direct contact between the concrete and the groundwater in the host rock, and the solubility of the porewater is set taking into account the change in solution composition from Region I to Region II (see "Reduction of radioactive material dissolution" in "Safety features of the geological environment"). • Consider migration only of RNs dissolved in porewater. • See the Table 6.3-6 for the handling of migration in the waste package, infill and structural framework • For the infill between waste packages in Grs.2 and 4H, there is uncertainty in the sorption by cement hydrates that have been altered by higher temperature, so such sorption is conservatively excluded from the model. • With regard to infill in the waste package of Grs.1 and 4L, consider sorption to cement hydrate and set appropriate distribution coefficient. • For Gr.3, consider the influence of nitrate when setting the distribution coefficients for cement hydrate.
Vault infill	RN sorption	• Same as fill within waste packages.	• Same as fill within waste packages.

Components	Safety function	Assumed most likely state	Concept of handling in RN migration analysis
Buffer	Prevention of RN migration by advection	• Alteration of buffer at contacts to concrete is restricted to the interface and, since most parts are sound, low hydraulic conductivity is assured and RN migration is dominated by diffusion, so the safety function is maintained. • The buffer deforms due to settling of the vault structure; the distribution of bentonite density changes, but the safety function is maintained by the design specifications.	• Model only RN migration by diffusion.
	Prevention of colloid migration	• Alteration of buffer at contacts to concrete is restricted to the interface and, since most parts are sound, low hydraulic conductivity is assured and RN migration is dominated by diffusion, so the safety function is maintained. • The buffer deforms due to settling of the vault structure; the distribution of bentonite density changes, but the safety function is maintained by the design specifications.	• Migration of colloids is not considered.
	RN sorption	• The buffer porewater is assumed to be in equilibrium with the bentonite, defining its sorption properties. • Depending on groundwater chemistry, ion exchange of montmorillonite occurs and the sorption properties change.	• Consider alteration of bentonite from Na-type to Ca-type according to the groundwater chemistry when setting the RN sorption parameters. • Consider changes in the ionic strength of the buffer porewater due to reaction with groundwater when setting the RN sorption parameters.
Geological environment	Protection from significant impacts of natural perturbations	• Site selection will exclude areas where such risk is significant.	• By definition not considered in these scenario.
	Reduction of RN dissolution	• Due to the reaction between buffer and groundwater, the composition of buffer porewater changes with time. • Depending on the inflow of ground water, cement porewater evolves from Region I to Region II. • The concentrations of RNs in porewater are limited at their solubility, set for porewater; RNs exceeding the solubility limits are precipitated. • The near field temperature is host rock ambient and the solubility limits are defined for this.	• Set solubility in consideration of temporal and spatial variability of EBS porewater. • The solubility is set taking into consideration the evolutions of the cement porewater from the Region I to the Region II. • Consider migration only of RNs dissolved in porewater.

Components	Safety function	Assumed most likely state	Concept of handling in RN migration analysis
	RN sorption	• The influence of high alkaline plume originating from concrete is limited to the vicinity of the vault and sorption performance is maintained in other areas.	• Do not consider the effect of high pH in setting the RN migration parameters of host rock. • Model sorption with Kd.
		• Nitrate contained in Gr.3 results in a plume influencing downstream groundwater chemistry.	• It is assumed that nitrate influences only the host rock downstream of Gr.3, influencing the Kds selected.
	RN dispersion	• RNs are dispersed by a network of fractures of different sizes, orientations and hydraulic properties.	• Model the flow and migration in multiple realisations of stochastically generated DFNs. The average transport characteristics were set with statistically generated DFN. • For the Neogene sediments, flow and migration though the porous rock between the fractures is also considered.
	Retardation of RN migration due to slow groundwater flow velocity	• A slow groundwater flow field is maintained. • Slow advective flow occurs through the matrix and/or structural discontinuities. • An EDZ is generated near tunnels and hydraulic conductivity in this region is higher. • The EDZ is mechanically stable over this time and remains highly permeable, although it is subject to stresses on the rock mass due to swelling of the buffer and corrosive expansion of the iron-based components [65].	• Apply a constant hydraulic gradient and hydraulic conductivity. • Set the EDZ width and hydraulic conductivity in the 3D transport model.

Table 6.3-7 Analysis of components within the TRU waste base scenario (T3: period after releases of RNs occur during which the characteristics of the geological environment are considered not to have significantly changed) (2/2)

Components	Safety function	Assumed most likely state	Concept of handling in RN migration analysis
Hydraulic plug, Backfill material	Prevention of tunnels acting as short-circuit routes for RN migration	• Swelling backfill seals gaps between it and the tunnel wall. • When concrete is present, the backfilling material deteriorates due to high pH leachate and hydraulic conductivity increases. • Alteration of the hydraulic plug is limited and the desired performance is maintained.	• The backfill hydraulic conductivity is set considering the extent of alteration, depending on the amount of concrete used. • The hydraulic plug is treated assuming its designed function is assured.
Structural framework	-	• In the structural framework, leaching of the concrete occurs gradually as the groundwater infiltrates. • For low salinity groundwater, the internal rebar has a passive film, so the corrosion rate is extremely low and new cracks due to corrosion expansion do not occur to a significant extent during re-saturation. • Corrosion of the rebars is faster in high salinity groundwater, cracks occur due to corrosion expansion, and the hydraulic conductivity increases.	• Consider temporal changes of structural framework hydraulic conductivity. • Set the high hydraulic conductivity in high salinity groundwater immediately after closing.
Mechanical plug	-	• Corrosion expansion of rebars increases cracks in concrete and increases hydraulic conductivity. • Complete leaching of the cementitious material and localised hydraulic conductivity increase.	• Because it is a local structure, the influence on the groundwater flow field is considered to be limited, and is not incorporated into the model.
Permeable layer (crushed rock)	-	• After backfilling, it exists as a highly permeable feature.	• Because it is a local structure, the influence on the groundwater flow field is considered to be limited, and is not incorporated into the model.
Filter material (glass fibre)	-	• Complete dissolution of the glass fibre.	• Because it is a local structure, the influence on the groundwater flow field is considered to be limited, and is not incorporated into the model.
Drain pipe	-	• Complete decomposition of the synthetic resin. • The expected decomposition products of the synthetic resin drain pipe have little complexation with RNs, so their influence is negligible [64]. However, the potential impact of such degradation would need re-assessment when materials are selected in future designs.	• Because it is a local structure, the influence on the groundwater flow field is considered to be limited, and is not incorporated into the model. • Since the decomposition products of the drain pipe are distant from the RN source, treat as having no influence on the barrier performance.
Buried formwork (glass fibre reinforced concrete)	-	• Complete dissolution of the glass fibre. • Leaching of concrete progresses, and any concrete component disappears.	• Because it is a local structure, the influence on the groundwater flow field is considered to be limited, and is not incorporated into the model.

Shotcrete	-	• Complete leaching of the cementitious material and localised hydraulic conductivity increase.	• Considering the uncertainty of rate of alteration, in the 3D groundwater flow analysis model, assume complete degradation at the time of first RN release.
Concrete liner	-		
Concrete invert	-		
Steel support (Neogene sediments)	-	• Corrosion under reducing conditions is slow and generated hydrogen gas is assumed to dissolve in groundwater and migrate into the surrounding host rock. • The effect on the EBS as a result of volume increase due to corrosion products is judged to be negligible.	• Alteration is limited and, since the altered part does not become a continuous structure, it is not included in the model.
Rock bolts	-	• Eventually the rock bolts will completely corrode, fixing material will completely leach and hydraulic conductivity will increase.	• Although the hydraulic conductivity increases, since it does not have a continuous structure, the influence on the groundwater flow field is small and is not incorporated into the model.
Grout	-	• Leaching of grout proceeds, possibly increasing hydraulic conductivity locally.	• Considering the uncertainty in the leaching rate, assume complete degradation and ignore any effect of reduced hydraulic conductivity of EDZ due to grout.
Waterproof sheet	-	• Complete decomposition of the synthetic resin. • The expected decomposition products of the synthetic resin waterproof sheet have little complexation with RNs, so their influence is negligible [64]. However, the potential impact of such degradation would need re-assessment when materials are selected in future designs.	• Since the decomposition products of the waterproof sheet are distant from the RN source, treat as having no influence on the barrier performance.
Central drain pipe	-	• Leaching of concrete infill progresses until closure. • After backfilling, it exists as a highly permeable feature.	• Consider hydraulic conductivity equivalent to sand.
Drain	-	• After backfilling, it exists as a highly permeable feature.	• Consider hydraulic conductivity equivalent to sand.

(2) Setting of analysis cases for variant scenarios

Following the RN migration approach for constituent repository elements in the base case, these are defined for variant cases in Table 6.3-8 and Table 6.3-9 for HLW and TRU waste, respectively. It is recognised that the current scenario selection is greatly simplified and will need to be revised in the future, when more realistic assessment will handle information for actual sites and consider repository concepts adapted to these sites.

Based on this material, Table 6.3-10 summarises the analysis cases derived for variant scenarios, along with associated assumptions and simplifications introduced for the RN migration analysis. In Table 6.3-10, as described in Section 6.1.5 (2), not only variants in the assumed evolution of the repository are presented, but also alternative evaluation models and datasets to the base case. As described in Section 6.2.2, due to current constraints, conservative simplifications are introduced when setting both the base and variant scenarios. Cases that combine variant options are not considered in this report, but will be examined in the future.

Table 6.3-8 Handling of analysis cases within the HLW variant scenarios (T3: period after releases of RNs occur during which the characteristics of the geological environment are considered not significantly changed) (1/2)

Component	Safety function	Uncertainties or perturbation of the model or data set to be considered	Concept of handling in RN migration analysis
Glass	Reduction of elution by glass matrix	• The following uncertainty may increase the dissolution rate of the glass: - Uncertainty of initial fracturing - Uncertainty in cracking due to external stress from overpack corrosion - Uncertainty concerning the influence of iron corrosion products and buffer on glass dissolution.	• Study impacts of different glass dissolution rates. This analysis case is referred to as the "Increase in glass dissolution case (HLW)".
Overpack	Prevention of contact between waste and groundwater	• Uncertainty is taken into account in the base scenario.	• Included in the base scenario.
Buffer	Prevention of RN migration by advection	• Consider uncertainties in diffusion coefficient measurement data.	• Vary buffer effective diffusion coefficients: "Increased diffusivity in buffer case (HLW) ".
	Prevention of colloid migration	• As a result of the impact analysis on the safety function, the buffer should assure no colloid migration. • However, at least for time scales beyond 100 ky, buffer performance could degrade (e.g. due to chemical erosion by dilute waters). Such a change is not considered here, but the long-term stability of the buffer might need further study in the future.	-
	RN sorption	• Consider uncertainties in RN sorption and diffusion coefficient measurement data.	• Vary buffer distribution coefficients: "Lower sorption in buffer case (HLW)".
Geological environment	Protection from significant impacts of natural perturbations	• As a result of the impact analysis on the safety function, performance should be assured for the first 100 ky. Impacts of likely geosphere evolution for longer time periods are not yet considered (see Supporting Report 6-10).	-
	Reduction of RN dissolution	• Consider uncertainty on thermal effects on solubility. • Consideration of the uncertainty in the assumption of thermodynamic equilibrium and completeness of the thermodynamic database (TDB).	• Vary solubility: "Thermal increase in solubility case (HLW)". • Vary solubility: "Uncertainty in thermodynamic data case (HLW)".
	RN sorption	• Consider uncertainties in measured sorption distribution coefficient and diffusion coefficient data and other uncertainties in modelling these processes.	• Vary distribution coefficients and effective diffusion coefficients: " Lower sorption in host rock case (HLW)", "Increased diffusivity in host rock case" (HLW).

Component	Safety function	Uncertainties or perturbation of the model or data set to be considered	Concept of handling in RN migration analysis
		• Consider the uncertainty concerning the nitrate plume from TRU waste as well as impacts from microbial activity on sorption.	• Vary distribution coefficients: "Nitrate plume impact case (HLW)".
	RN dispersion	• Consider uncertainty concerning the hydraulic conductivity of the probabilistic fracture network on the degree of dispersion.	• The fracture network realisation with the fastest mass transfer is used in the analysis case: "Fracture connectivity in host rock case".
	Retardation of RN migration due to slow groundwater flow velocity	• Consider uncertainty concerning the hydraulic conductivity of the probabilistic fracture network on the water velocity.	• As above, the fracture network realisation with the fastest mass transfer is used in the analysis case: "Fracture connectivity in host rock case".
Hydraulic plug, backfill material	Prevention of tunnels acting as short-circuit routes for RN migration	• Even if uncertainty is considered, the desired performance of the hydraulic plug is assumed to be maintained. • When cementitious materials surround backfill, hydraulic conductivity may increase more rapidly if uncertainty in the reactions between them is taken into consideration.	• Such uncertainty is included in the analysis case for the base scenario, because it is set taking into account such degradation.

Table 6.3-8 Handling of analysis cases within the HLW variant scenarios (T3: period after releases of RNs occur during which the characteristics of the geological environment are considered not to have significantly changed) (2/2)

Component	Safety function	Uncertainties or perturbation of the model or data set to be considered	Concept of handling in RN migration analysis
Mechanical plug	-	• The corrosion of rebars and dissolution of cementitious materials is almost complete during the period T2, which can be regarded as equivalent to the most probable state (see Table 6.35), taking into account the uncertainty of corrosion and concrete dissolution rates.	• Even considering such uncertainties, impacts are localised and the influence on the groundwater flow field is considered to be limited, so assumed covered by the base scenario.
Permeable layer (crushed rock)	-	-	• Covered by base scenario analysis cases.
Buried formwork (glass fibre reinforced concrete)	-	• Consider the uncertainty of the dissolution rate of the glass fibre. • Consider the uncertainty of the leach rate of cementitious material and thus the time of its complete loss.	• Even considering such uncertainties, impacts are localised and the influence on the groundwater flow field is considered to be limited, so assumed covered by the base scenario.
Filter material (glass fibre)	-	• Consider the uncertainty of the dissolution rate of the glass fibre.	• Even considering such uncertainties, impacts are localised and the influence on the groundwater flow field is considered to be limited, so assumed covered by the base scenario.
Drain pipe	-	• Consider the uncertainty of its decomposition rate and thus the time of its complete loss.	• Even considering such uncertainties, impacts are considered negligible, so assumed covered by the base scenario.
Shotcrete	-	• Consider the uncertainty of the leach rate of cementitious material and thus the time of its complete loss. • Consider uncertainty in the construction quality, so may be locally high hydraulic conductivity.	• Such uncertainty is included in the analysis case corresponding to the base scenario, because it is set taking into account such degradation.
Concrete liner	-		
Concrete invert	-		
Steel support Neogene sediments)	-	• Consider the uncertainty of the corrosion rate of the support, and thus the time of its complete loss.	• Even considering such uncertainties, impacts are localised and the influence on the groundwater flow field is considered to be limited, so assumed covered by the base scenario.

Component	Safety function	Uncertainties or perturbation of the model or data set to be considered	Concept of handling in RN migration analysis
Rock bolts	-	• Consider the uncertainty of the corrosion rate, and thus the time of its complete loss. • Consider the uncertainty of the leach rate of cementitious fixing material and thus the time of its complete loss.	• Even considering such uncertainties, impacts are localised and the influence on the groundwater flow field is considered to be limited, so assumed covered by the base scenario.
Grout	-	• Consider the uncertainty of the leach rate of cementitious material and thus the time of its complete loss. • Consider uncertainty in the construction quality, so may be locally high hydraulic conductivity.	• Such uncertainty is included in the analysis case corresponding to the base scenario, because it is set taking into account such degradation.
Waterproof sheet	-	• Consider the uncertainty of the decomposition rate of the waterproof sheet and thus the time of its complete loss.	• Even considering such uncertainties, impacts are considered negligible, so assumed covered by the base scenario.
Drain	-	• Consider the uncertainty of the leach rate of cementitious material and thus the time of its complete loss. • Consider uncertainty in the construction quality, so may be locally high hydraulic conductivity.	• Such uncertainty is included in the analysis case corresponding to the base scenario, because it is set taking into account such degradation.
PEM handling shell	-	• Consider the uncertainty of the corrosion rate of the support, and thus the time of its complete loss.	• Such uncertainties do not impact the safety functions of the buffer and backfill, so this is covered by the base scenario.

Table 6.3-9 Handling of analysis cases within the TRU variant scenarios (T3: period after releases of RNs occur during which the characteristics of the geological environment are considered not significantly changed) (1/2)

Component	Safety function	Uncertainties considered	Concept of handling in RN migration analysis
Waste package	Reduction of RN elution	• Consider the uncertainty of steel corrosion rate and the associated time of failure of containment. • Consider the following uncertainties in the corrosion rate of Gr.2 metal waste: - For Zircaloy, uncertainties concerning the effects of temperature and hydrogen - For stainless steel, uncertainty regarding the influence of temperature. • Consider the uncertainty of the concrete leach rate, thermal degradation and the effect by nitrate and its impact on RN sorption.	• Covered by the base scenario for waste package A, since the time until elution of the RNs is ignored. • Vary corrosion rate of Gr.2 metal waste: “Increased corrosion of TRU Gr.2 case (TRU waste)”.
Vault infill	RN sorption	• Consider the uncertainty of the leach rate of concrete and its impact on RN sorption.	• Due to uncertainty in the evolution from Region I to Region II, the lower Kd value for these bounding cases is already conservatively selected for the base case.
Buffer material	Prevention of RN migration by advection	• Consider uncertainties in diffusion coefficient measurement data.	• Vary buffer effective diffusion coefficient: “Increased diffusivity in buffer case (TRU waste)”.
	Prevention of colloid migration	• As a result of the impact analysis on the safety function, the buffer should assure no colloid migration. • However, at least for time scales beyond 100 ky, buffer performance could degrade (e.g., due to chemical erosion by dilute waters). Such a change is not considered here, but the long-term stability of the buffer might need further study in the future.	• -
	RN sorption	• Consider uncertainties in RN sorption and diffusion coefficient measurement data.	• Vary buffer distribution coefficient: “Lower sorption in buffer case (TRU waste)”.
Geological environment	Protection from significant impacts of natural perturbations	• As a result of the impact analysis on the safety function, performance should be assured for the first 100 ky. Impacts of likely geosphere evolution for longer time periods are not yet considered (see Supporting Report 6-10).	• -

Component	Safety function	Uncertainties considered	Concept of handling in RN migration analysis
	Reduction of RN dissolution	• Consider uncertainty on thermal effects on solubility. • Consideration of the uncertainty in the assumption of thermodynamic equilibrium and completeness of the TDB.	• Vary solubility: "Thermal increase in solubility case (TRU waste)". • Vary solubility: "Uncertainty in thermodynamic data case (TRU waste)".
	RN sorption	• Consider uncertainties in measured sorption distribution coefficient and diffusion coefficient data and other uncertainties in modelling these processes.	• Vary distribution coefficients and effective diffusion coefficients: "Lower sorption in host rock case (TRU waste)", "Increased diffusivity in host rock case (TRU waste)".
		• Consider the uncertainty concerning the nitrate plume from TRU waste as well as impacts from microbial activity on sorption.	• Vary distribution coefficients: "Nitrate plume impact case (TRU waste)".
	RN dispersion	• Consider uncertainty concerning the hydraulic conductivity of the probabilistic fracture network on the degree of dispersion.	• The fracture network realisation with the fastest mass transfer is used in the analysis case: "Fracture connectivity in host rock case".
	Retardation of RN migration due to slow groundwater flow velocity	• Consider uncertainty concerning the hydraulic conductivity of the probabilistic fracture network on the water velocity.	• As above, the fracture network realisation with the fastest mass transfer is used in the analysis case: "Fracture connectivity in host rock case".
Hydraulic plug, Backfill material	Prevention of tunnels acting as short-circuit routes for RN migration	• Even if uncertainty is considered, the desired performance of the hydraulic plug is assumed to be maintained. • When cementitious materials surround backfill, hydraulic conductivity may increase more rapidly if uncertainty in the reactions between them is taken into consideration.	• Such uncertainty is included in the analysis case corresponding to the base scenario, because it is set taking into account this degradation.
Structural framework	-	• Corrosion of rebars and dissolution of concrete components are almost complete during T2, except in low salinity groundwater where these processes are considered to be less rapid (see Table 6.3 7). • In the case of low and high salinity groundwater in plutonic rock, degradation due to alteration may progress to a highly permeable state at an early stage, taking into account uncertainties such as the state of cracking that occurs during construction and the rate of leaching of concrete components.	• Assume deterioration of the structural framework when setting its hydraulic conductivity: "Uncertainty in structural frame degradation case (TRU waste)".

Table 6.3-9 Handling of analysis cases within the TRU variant base scenario (T3: period after releases of RNs occur during which the characteristics of the geological environment are considered not significantly changed) (2/2)

Component	Safety function	Uncertainties considered	Concept of handling in RN migration analysis
Mechanical plug	-	• Consider the uncertainty in the corrosion rate of the rebars and thus hydraulic conductivity due to resulting cracks. • Consider the uncertainty of the leach rate of cementitious material and thus the time of its complete loss.	• Even considering such uncertainties, impacts are localised and the influence on the groundwater flow field is considered to be limited, so assumed covered by the base scenario.
Permeable layer (crushed rock)	-	• -	• Covered by base scenario analysis cases.
Filter material (glass fibre)	-	• Consider the uncertainty of the dissolution rate of the glass fibre. • Consider the uncertainty of the leach rate of cementitious material and thus the time of its complete loss.	• Even considering such uncertainties, impacts are localised and the influence on the groundwater flow field is considered to be limited, so assumed covered by the base scenario.
Drain pipe	-	• Consider the uncertainty of the decomposition rate and thus the time of complete loss.	• Even considering such uncertainties, impacts are localised and the influence on the groundwater flow field is considered to be limited, so assumed covered by the base scenario.
Buried formwork (glass fibre reinforced concrete)	-	• Consider the uncertainty of its decomposition rate and thus the time of its complete loss.	• Even considering such uncertainties, impacts are considered negligible, so assumed covered by the base scenario.
Shotcrete	-	• Consider the uncertainty of the leach rate of cementitious material and thus the time of its complete loss. • Consider uncertainty in the construction quality, so may be locally high hydraulic conductivity.	• Such uncertainty is included in the analysis case corresponding to the base scenario, because it is set taking into account such degradation.
Concrete liner	-		
Concrete invert	-		
Steel support (Neogene sediments)	-	• Consider the uncertainty of the corrosion rate of the support, and thus the time of its complete loss.	• Even considering such uncertainties, impacts are localised and the influence on the groundwater flow field is considered to be limited, so assumed covered by the base scenario.
Rock bolts	-	• Consider the uncertainty of the corrosion rate, and thus the time of its complete loss.	• Even considering such uncertainties, impacts are localised and the influence on the groundwater flow field is considered to be limited, so assumed covered by the base scenario.

Component	Safety function	Uncertainties considered	Concept of handling in RN migration analysis
		• Consider the uncertainty of the leach rate of cementitious fixing material and thus the time of its complete loss.	
Grout	-	• Consider the uncertainty of the leach rate of cementitious material and thus the time of its complete loss. • Consider uncertainty in the construction quality, so may be locally high hydraulic conductivity.	• Such uncertainty is included in the analysis case corresponding to the base scenario, because it is set taking into account such degradation.
Waterproof sheet	-	• Consider the uncertainty of the decomposition rate of the waterproof sheet and thus the time of its complete loss.	• Even considering such uncertainties, impacts are considered negligible, so assumed covered by the base scenario.

Table 6.3-10 Overview of Analysis Cases (1/2)

Analysis case name	Handling in the base and variant cases		Plutonic		Neogene		Pre-Neogene	
			Low	High	Low	High	Low	High
Increase in glass dissolution case (HLW)	Base	Apply a glass dissolution model using the long-term dissolution rate, taking into account the increase in the area due to cracking during fabrication.	✓	✓	✓	✓	✓	✓
	Variant	Consider the following uncertainties to set increases in the dissolution rate of the glass • Uncertainty in cracking due to external stress from overpack corrosion • Uncertainty on the impacts of iron corrosion products and buffer.						
Increased corrosion of TRU Gr.2 case (TRU)	Base	For Gr.2 metal wastes, the RNs are leached congruently with the corrosion of the metal, depending on the corrosion rate.	✓	✓	✓	✓	✓	✓
	Variant	Consider uncertainties in measurement data, set increased corrosion rates.						
Uncertainty in structural frame degradation case (TRU)	Base	Change the hydraulic conductivity of the structural framework with time.	✓	✓	✓	*	✓	*
	Variant	Consider uncertainty in the degree of cracking at the time of construction and the leach rate; set hydraulic conductivity assuming degraded structure from the beginning.						
Nitrate plume impact case (HLW/TRU)	Base	Set host rock RN migration parameters assuming nitrate affects TRU waste Gr.3.	✓	✓	✓	✓	✓	✓
	Variant	Consider uncertainty in the spread of the nitrate plume and set host rock RN migration parameters assuming nitrate affects waste located parallel to Gr.3 with respect to groundwater flow direction.						
Fracture connectivity in host rock case (HLW/TRU)	Base	The average migration rate calculated from the probabilistic discrete fracture network (DFN).	✓	✓	✓	✓	✓	✓
	Variant	Consider uncertainty in the DFN and apply the realisation giving fastest migration (evaluated using the time until maximum migration rate of the tracer at the outlet reached).						

Table 6.3-10 Overview of Analysis Cases (2/2)

Analysis case name	Handling in the base case (upper row) and Handling in variant case (lower row)		Plutonic		Neogene		Pre-Neogene	
			Low	High	Low	High	Low	High
Lower sorption in buffer case (HLW/TRU)	Base	Apply the average value of measured apparent diffusion coefficients and effective distribution coefficient for specified buffer and porewater chemistry using an empirical formula based on Fickian assumptions	✓	✓	✓	✓	✓	✓
	Variant	Consider uncertainties in measured data and set lower sorption coefficients in the database						
Increased diffusivity in buffer case (HLW/TRU)	Base	Apply the average value of the database of effective diffusion coefficients for specified buffer and porewater chemistry	✓	✓	✓	✓	✓	✓
	Variant	Consider uncertainties in measured data and set higher diffusion coefficients in the database						
Lower sorption in host rock case (HLW/TRU)	Base	Apply the average value of the database of sorption distribution coefficients for specified rock and groundwater chemistry	✓	✓	✓	✓	✓	✓
	Variant	Consider uncertainties in measured data and set lower sorption coefficients of 95% confidence interval in the database						
Increased diffusivity in host rock case (HLW/TRU)	Base	Apply the average value of measured diffusion coefficients for specified rock and groundwater chemistry	✓	✓	✓	✓	✓	✓
	Variant	Consider uncertainties in measured data and set higher diffusion coefficients in the database						
Thermal increase in solubility case (HLW/TRU)	Base	It is assumed that the influence of the temperature on solubility is negligible	✓	✓	✓	✓	✓	✓
	Variant	Taking into consideration the uncertainty of solubility with respect to possible repository temperatures, set a higher solubility						
Uncertainty in thermodynamic data case (HLW/TRU)	Base	Apply the derived solubility limits calculated from the thermodynamic database	✓	✓	✓	✓	✓	✓
	Variant	Consider associated uncertainties and set higher solubility limits	✓	✓	✓	✓	✓	✓

High: high salinity groundwater, Low: low salinity groundwater, ✓: application to variant cases
HLW: HLW repository only, TRU: TRU waste repository only, HLW/TRU: applicable to both repositories
* Since the salinity in the groundwater is high, corrosion of the steel rebars in the structural concrete progresses during the operation period, and it is considered that the hydraulic conductivity increases due to cracks associated with such corrosion; hence, even in the base cases, the hydraulic conductivity is set to be high from the beginning of the assessment.

(3) Setting the analysis cases for low probability perturbation scenarios

Table 6.3-11 outlines the low probability perturbation scenarios and the calculational approach to dose evaluation in the corresponding analysis cases. This concerns new volcanism and fault activity.

For the fault perturbation scenarios (see Section 6.3.2 (3) (iii)), the area of the repository significantly affected is inherently limited in the fault consolidation scenario (Supporting Reports 3-35). However, the uncertainty associated with the fault extension scenario is large and it is difficult to reliably establish the area of the repository impacted; thus, in both the HLW and TRU waste analysis cases, the entire area of the repository is conservatively assumed to be affected. For dose assessment, only the analysis cases for fault extension scenarios, in which more waste is affected, are considered.

Table 6.3-11 Analysis cases for low probability perturbation scenarios

Scenario/analysis case	Overview	Treatment in analysis cases
New volcano	Consider the possibility that a new volcano will develop and directly affect the repository	• A new volcano occurs and magma directly intrudes into the repository. • RNs in the area directly hit by the volcanic conduit reach the surface of the Earth with the ejecta. • Assume the ejecta containing radioactive material is deposited on the surface and mixes with existing soil: calculate the dose to local inhabitants.
Fault consolidation	Consider the possibility relatively small faults consolidate and impact the repository	• This scenario and the fault extension scenario are common in the sense that the fault extends and affects the repository, and the evaluation conditions are set so that the analysis case corresponding to the fault extension scenario includes the analysis case corresponding to this scenario.

Fault extension	Consider the possibility that a fault grows to impact the repository	• Conservatively define the area affected by the extended fault.
		• The fault and associated process zone gradually increase as the fault grows, so it is unlikely that these areas will develop with one event [66]. However, conservatively assume immediate formation in a single growth event.
		• Safety functions of EBS and host rock in the HLW repository are handled:
		  o The overpack, buffer material and surrounding host rock located on the fault plane and in the area of the fault zone are damaged by the fault extension and lose their safety functions. It is assumed that the dissolution rate of the vitrified waste in the fault zone increases with the increase in groundwater flow rate and the dissolution rate of the vitrified waste in the fault plane increases with the increase in groundwater flow rate.
		  o For engineered barriers located in the process zone, there is little influence on the safety function. The safety function of the surrounding host rock is not taken into account because it is difficult to quantify the increase in its hydraulic conductivity.
		• Safety functions of EBS and host rock in the TRU repository are handled:
		  o For disposal tunnels directly struck by an extensional fault, RNs from all waste packages will leach instantly into groundwater and migrate directly to the extensional fault, except for Gr.2.
		  o In the case of Gr.2, RNs contained in metal parts will leach out and migrate to the fault due following congruent corrosion.
		• For the waste affected, all released RNs are transported to the GBI via the fault.
		• This fault is treated as a porous medium in which sorption of RNs is considered.
		• Set GBI and biosphere as for the base case scenario.

6.4 Radionuclide migration analysis and dose assessment

In this section, the RN migration analysis models and associated datasets are introduced for each of the scenario analysis cases, plus dose conversion factors to allow releases to the biosphere to be compared with established targets.

As noted in Section 6.3, RN migration models are applicable to several analysis cases, while dose conversion factors are generally applicable. Datasets, however, tend to differ according to the scenario involved. Section 6.4.1 describes the RN migration models, datasets and dose conversion factors used for the base case scenarios, while differences in the datasets used for the variant scenarios are summarised in Section 6.4.2. Finally, Section 6.4.3 describes the evaluation of the low probability perturbation scenarios.

6.4.1 RN migration analyses and dose evaluations of base scenario

(1) RN migration analyses for different spatial scales

In the H12 report, the focus of the safety assessment was identification of generic research and development needs and thus emphasis was on the performance of the HLW EBS and behaviour of the near field, which is relatively easy to study and characterise. This approach allowed demonstration of the fundamental feasibility of geological disposal of HLW in Japan, without specifying sites. The models used in the H12 report conservatively simplify the geometry of the EBS, the heterogeneity of RN migration pathways and routes through the geosphere, and the impacts of different host rocks. In addition, the barrier performance of overlying rocks between the host rock and the surface was not evaluated, with consideration of only a short-circuit migration route via a highly permeable fracture zone. Such approaches and analytical models were also used in the TRU-2 report.

As noted in Section 6.1.1, the intention here is to more realistically reflect the characteristics of the geological environment at sites represented by the SDMs, together with tailored repositories, as shown in Section 6.1.3. The approach to RN migration analysis used in this report for different spatial scales will now be described.

As indicated in Figure 6.4-1, at the near field scale, a 3D hydrogeological model is used that considers the design specifications of the EBS and heterogeneous properties of surrounding host rock. Here, since a diverse range of RNs are to be analysed, the 3D model is used to efficiently determine the fundamental characteristics of movement of groundwater, providing the boundary conditions to allow use of a simplified RN migration model (see Section 6.4.1 (2) (iv) below).

To model RN migration at the panel scale, both the EBS components and the panel layout in terms of disposal and access tunnels, together with the characteristics of immediately surrounding host rock, are taken into account. For complex RN migration analysis, the 3D near field model is established at the downstream end of disposal panels and assumed also to represent panels further upstream with longer flow paths. This extremely simple, conservative model is applied to calculate the release rate of RNs from each disposal panel into the surrounding host rock.

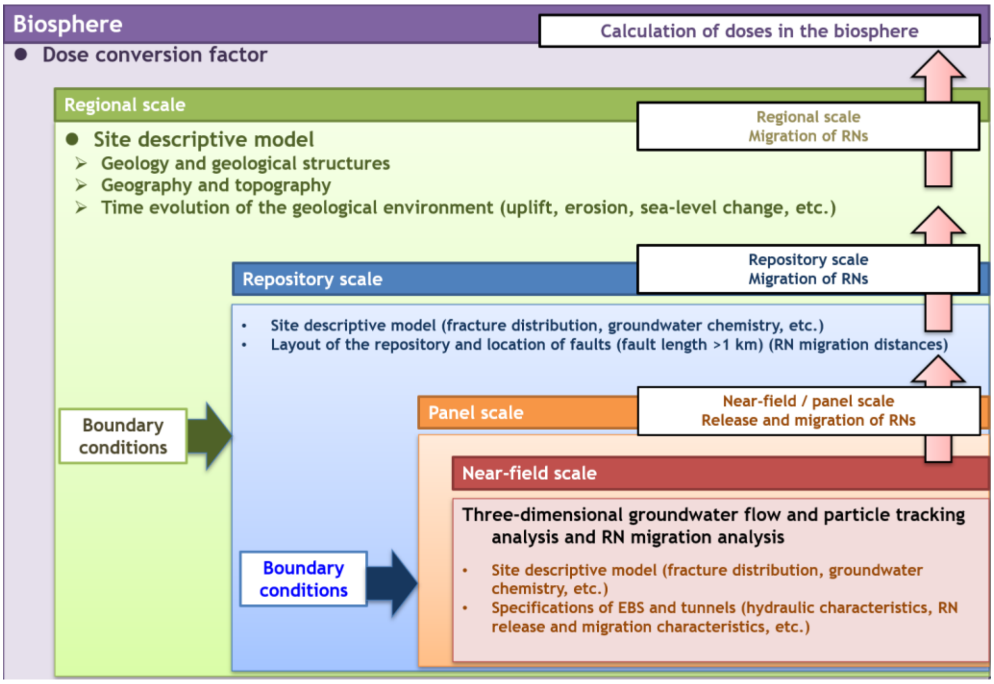


Figure 6.4-1 Concept of RN migration analysis illustrating how calculated RN release rates at one scale are passed on to the next spatial scale (hydro boundary conditions are defined from large to small scales)

On the repository scale, RNs released from each panel migrate through the host rock as determined by the local flow of the groundwater to an analysis boundary (usually the nearest downstream fault as defined by the SDM). Furthermore, it is assumed that this boundary represents a short circuit to the GBI via a major fault. It is recognised that this is a simplified conservative assumption that would be revised when specific sites are evaluated. Again, as in the near field scale, groundwater flow using a 3D model is analysed, which conditions a simplified RN migration analysis (See Section 6.4.1 (4) (i)).

At a regional scale, extending from the repository scale to the GBI, it is necessary to capture the characteristics and temporal changes of the topography, geological structure, surface environment, etc., and reflect these in the RN migration and biosphere evaluations. As already mentioned, this report follows the concepts used in the H12 and TRU-2 safety assessments, assuming that large-scale faults act as short-circuits to the biosphere. The biosphere model considers the GBI as the connection point between such large-scale faults and the surface water flow system. Simplistically, the radiation dose is calculated by multiplying RN release fluxes by dose conversion factors calculated for stylised biospheres; for the current assessment these are assumed not to change with time.

In the RN migration analysis described above, it is necessary to set the THMC boundary conditions for each spatial scale. For this, the following approach (see Figure 6.4-1) is adopted.

Based on the regional scale SDM, the THMC conditions at repository depth is set. These conditions are assumed to be reasonably uniform and stable on the repository scale.

In the near field and the panel scales, there will be perturbations of such conditions due to impacts of repository excavation and operation, heat generation from waste, EBS materials introduced, etc. (see Table 6.1-2). For TRU waste, the loss of containment is assumed to be early enough that thermal effects need to be considered when selecting migration data, in contrast to the HLW overpack containment which is lost only after the entire repository is at rock ambient temperature. The data set used for RN migration analysis also takes into consideration changes of groundwater composition and material properties over time.

Hydrogeological conditions at the repository scale boundaries are set based on the spatial distribution of hydraulic head obtained by regional scale groundwater flow analysis. Then, by analysing groundwater flow at the repository scale, boundary conditions are set for analysis of RN migration at panel and near field scales. This approach, which is commonly applied in such assessments in other countries, aims for hydraulic consistency between scales, with practical simplifications applied according to the scale of model (see Section 3.3.3).

Based on this approach, and the repository designs for each SDM presented in Chapter 4, the spatial domains for RN migration analysis considered for dose assessment are defined. Figure 6.4-2 shows an example based on a HLW repository layout option for plutonic rocks, assuming co-disposal of TRU waste.

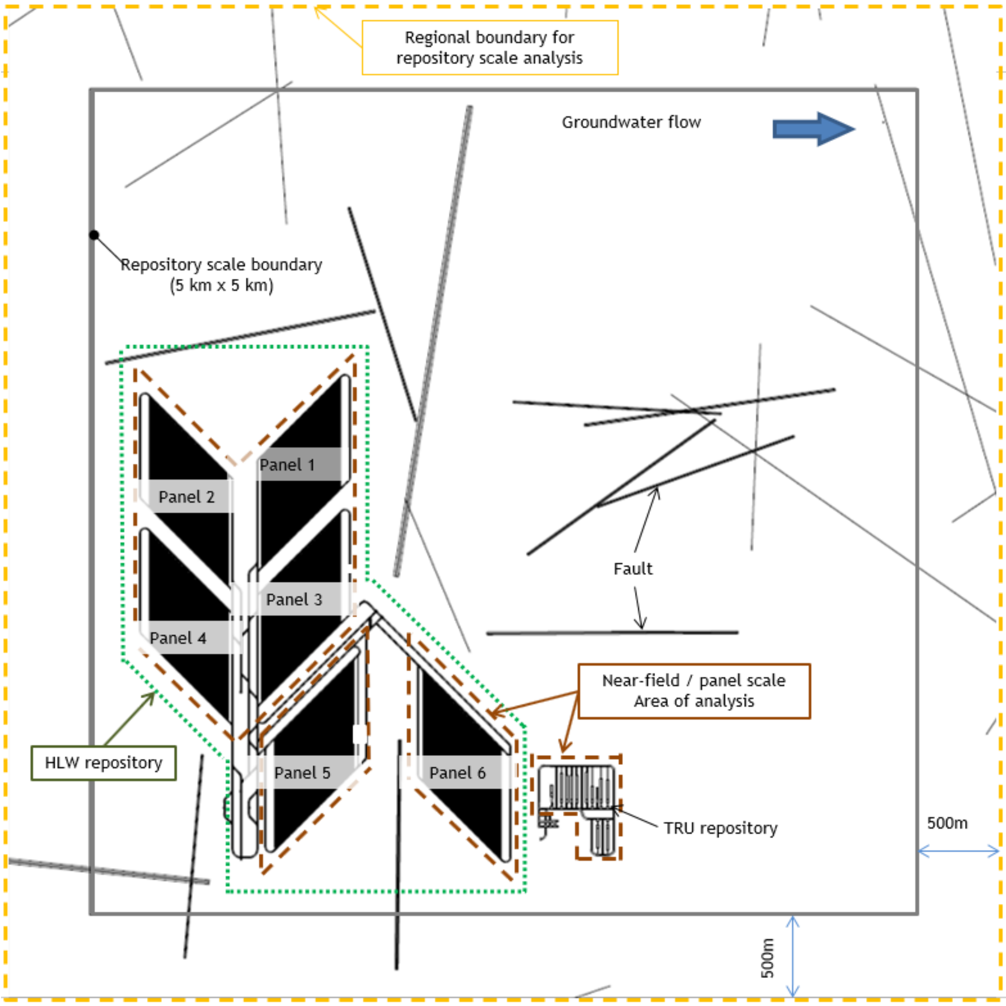


Figure 6.4-2 Setting spatial scales for RN migration analysis (HLW repository in plutonic rock (H12V) with co-located TRU repository).

It should be noted that in this figure the TRU repository is located downstream (for the current hydrogeological state) of HLW panels (thus avoiding any negative effects from the TRU repository on the barrier performance of the HLW repository), but this is potentially not optimised in relation to location of faults. In this Figure, the area surrounded by a dotted green line defines the area of EBS/host rock covered at the panel scale, which includes within it, the near field scale model within dashed brown lines, as explained in Section 6.4.1 (2) (ii) below.

As described in Section 3.3.3, analysis of groundwater flow at the repository scale (in the plane of the host rock covering an area of 5 km x 5 km) considers impacts of the distribution of major water-carrying faults on groundwater flow velocities and transport times, based on boundary conditions from the regional scale model. This extends beyond the area analysed on the panel scale, and is based on the SDMs, including an additional 500 m perimeter to allow transport routes in peripheral host rock to be captured in cases where the disposal footprint lies near a repository-scale model boundary. RN migration analysis at the repository scale is described in Section 6.4.1 (4).

As mentioned in Section 4.5.4, a planar area extending beyond the repository scale was set for each host rock (see Section 3.3.3 (3) (ii) (c): 10 km x 10 km for plutonic rocks and Pre-Neogene sediments; 7.5 km x 7.5 km in the case of Neogene sediments). This is used to define relative groundwater migration times from different disposal areas (see Supporting Report 4-49). The regional distribution of hydraulic head obtained from this groundwater flow analysis was used for migration modelling at repository, panel and near field scales and particle tracking analysis at repository and near field scales (6.4.1 (2) (iv) (b) and (4) (i)).

Using the analysis system described above, a more realistic RN migration assessment can be conducted, considering the EBS design and layout while maintaining practicality. An outline of the analysis codes used is given in Supporting Report 6-12. However, it should also be noted that the current model scales and their representations will be revisited and made less stylised when assessing real sites in the future.

(2) Near field scale model and dataset

(i) Basic model concept

3D groundwater flow and particle tracking analyses were conducted for the purpose of evaluating RN transfer paths, transport distances, flow rates, etc. in the near field scale region, based on the features of the EBS and surrounding host rock.

Chapter 4 provides detailed repository system designs in terms of 3D shapes and layouts, together with material specifications of tunnels and engineered barriers. These are specifically established on the basis of key SDM characteristics, such as spatial distributions of fractures, rock mechanics and hydraulic gradient, which influence RN migration behaviour (see Section 6.1.2 (1)).

For near field host rock, common features of the different SDMs are networks of distinct water-carrying features which can be simulated by discrete fracture network (DFN) models (see Section 3.3.3). Such models were constructed for all host rocks although, for Neogene sediments, an integrated model accounting for flow in both fracture networks and the porous matrix was developed.

The host rock modelling concept described above was implemented in the versatile calculation code "Partridge" [23] (see Section 6.4.1 (2) (iii) below). Partridge can simulate characteristics of both the EBS and near field host rocks in some detail, allowing particle track analysis by a 3D random walk method to quantify the mass transfer processes occurring. However, this requires a long calculation time and, therefore, a simplified RN migration model was developed, which allows more practical implementation of a large number of calculations targeting a wide variety of RNs for various scenarios. Figure 6.4-3 shows the procedure for near field modelling of RN migration analysis.

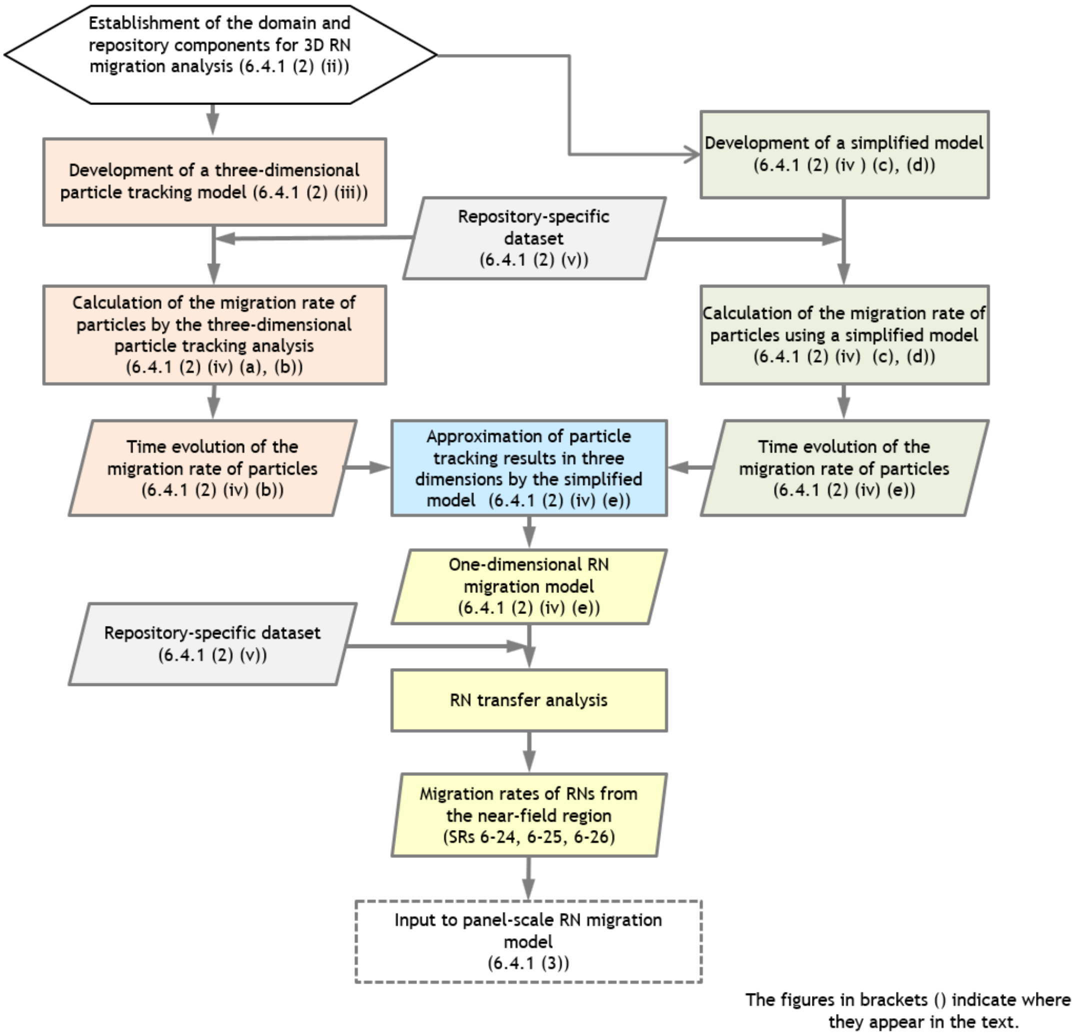


Figure 6.4-3 Procedure for analysis of RN migration in the near field

(ii) Analysis approaches and components of the models

For the HLW repository layout option for H12V in plutonic rocks (or Pre-Neogene sediments) and co-disposal of TRU shown in Figure 6.4-2, the structures to be assessed at a near field scale are shown in Figure 6.4-4. Note that the access tunnels are not included in the near field model, since the flow direction is perpendicular to the disposal tunnels/vaults and parallel to the access tunnels.

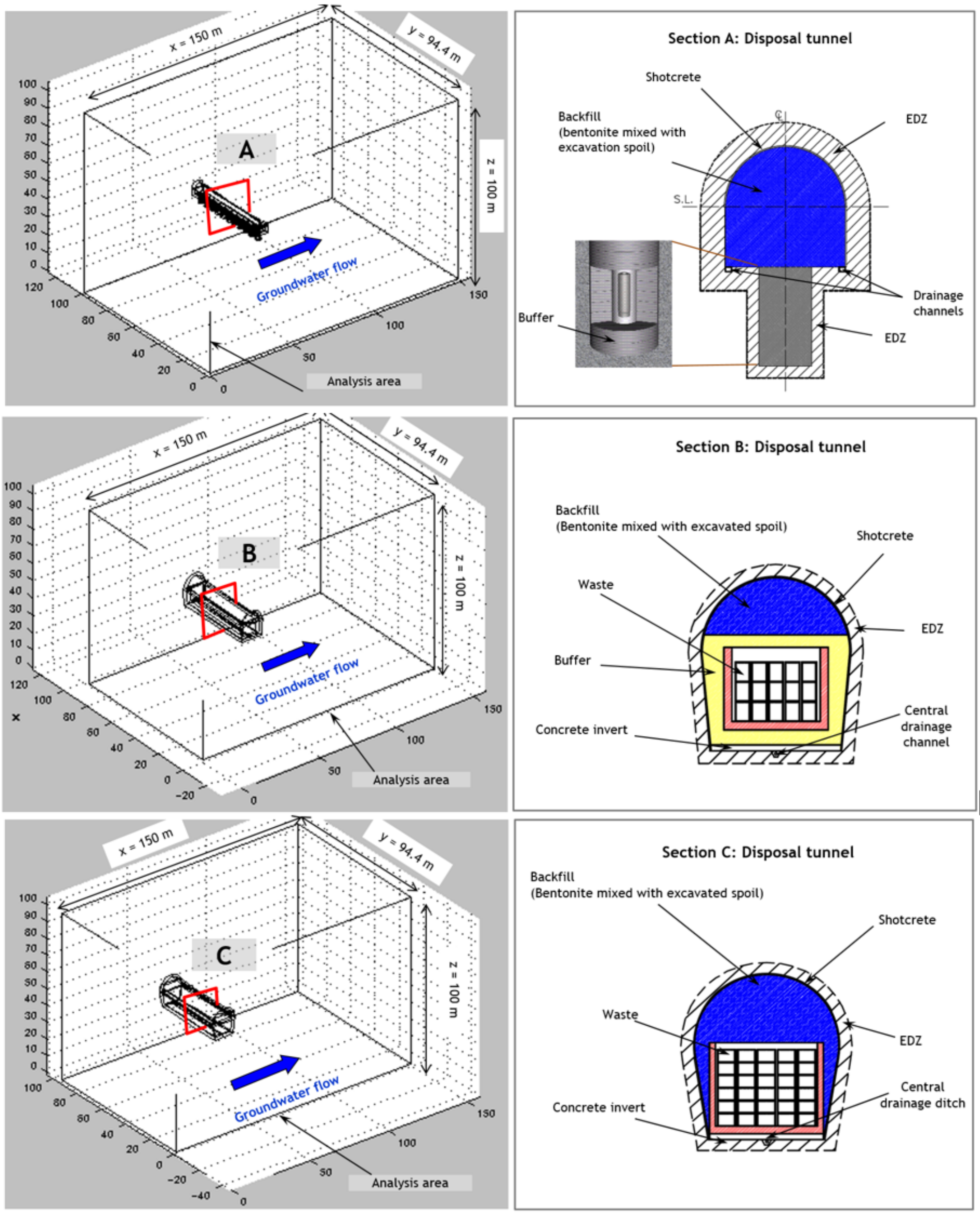


Figure 6.4-4 Repositories in plutonic rock or Pre-Neogene sediments: illustration of components for three-dimensional groundwater flow/ particle track analysis at the near field scale (a): HLW–H12V, (b): TRU waste Gr.2, (c): TRU waste Gr.3.

For the H12V option (Figure 6.4-4 (a)), the model to calculate the release rate of RNs includes 10 disposal holes, along a tunnel length of 44.4 m, and a volume of rock extending 100 m downstream. Here, the 100 m length of downstream host rock was set from the viewpoint of practicality, based on the capabilities of the Partridge code used.

The shape and size of the tunnel cross-sections and component materials are specified in Section 4.5.2. In the assessment model, the EDZ is modelled as a mixed tank defined by its volume and porosity. The EDZ for the H12V option components is set on the basis of the excavation methods assumed (see Supporting Report 4-44, 4-67), resulting in the characteristics and thicknesses used for the models (see Supporting Report 6-14).

For the HLW PEM option, the size of the analysed area is the same, but the length of disposal tunnel considered is 45.6 m, which contains 13 PEMs. Shapes and dimensions of the disposal tunnel are based on design specifications given in Section 4.5.2. EDZ dimensions and characteristics are defined in a similar manner to the H12V case.

Figures 6.4-4 (b), (c) illustrate the analysed systems for TRU waste. As described in Section 6.4.1 (2) (iv), for RN migration analysis, a simplified one-dimensional model is constructed based on the 3D particle tracking results as for the HLW case. For 3D particle tracking, a model reflecting the shape and characteristics of the repository components is used; however, for TRU waste, a range of different disposal vault cross-sections are defined for each host rock (see Supporting Report 4-36). Conditioned by the 3D particle tracking analysis, RN migration is approximated by a one-dimensional, multi-channel model (Section 6.4.1 (2) (iv). In order to capture key differences, representative disposal vaults for cases with and without buffer are modelled, selecting for these Grs.2 and 3, respectively, and defining associated EDZ characteristics as previously described for HLW. The analysed area is the same as the HLW case, with the vault length including three emplacement pits (Supporting Report 4-42).

For repositories in Neogene sediments (Figure 6.4-5), the representation is somewhat different, reflecting the fact that disposal tunnels/vaults are excavated parallel to the groundwater flow direction (see Section 4.5.4). RN migration paths intercept connecting tunnels at the downstream end of the disposal panel and thus these need to be handled explicitly. For HLW, five disposal tunnels were modelled, including the area of downstream host rocks extending 100 m from the last disposal hole. For the TRU waste disposal vaults, a similar procedure is adopted and the access tunnels downstream are included in the model. Again, representative disposal vaults were modelled for cases with and without buffer, selecting for these, Grs.2 and 3, respectively, and defining associated EDZ characteristics as previously described for HLW. The analysed area is the same as the HLW case, with the vault length including three emplacement pits (Supporting Report 4-42).

EDZ characteristics are defined as for plutonic rock, although it is understood the development and evolution of an EDZ in Neogene sediments may differ. Such differences will need to be explored further once specific sites are assessed. For Pre-Neogene sediments, the system components are the same as for plutonic rocks (Section 6.1.2, Figure 6.4-4) and hence the models and system representations within them are also the same as described above.

In all of the repositories for the host rock considered, components other than engineered barriers, such as backfill, shotcrete and other cementitious materials, were given conservatively high hydraulic conductivity values so that their influence on RN migration in the near field could be clearly taken into account, reflecting their alteration with time (see Table 6.3-3).

The 3D groundwater flow analyses are described in more detail in Supporting Report 6-14.

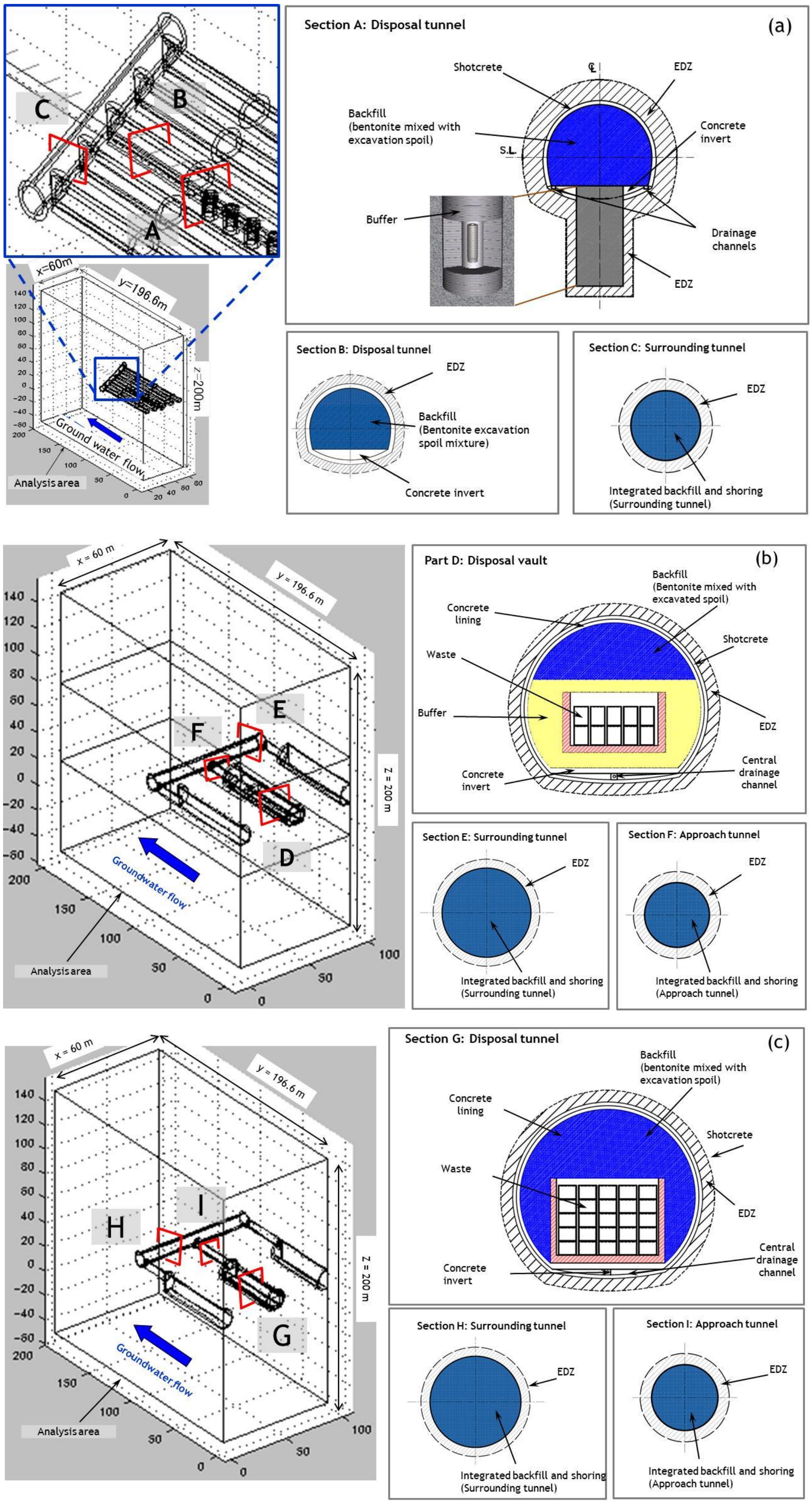


Figure 6.4-5 Repositories in Neogene sediments: illustration of components for the three-dimensional groundwater flow/particle track analysis at the near field scale, (a): HLW–H12V, (b): TRU waste Gr.2, (c): TRU waste Gr.3

(iii) Application of the 3D RN migration code Partridge

Partridge is a code developed for particle tracking analysis, reflecting features such as repository design and characteristics of a fractured host rock [23], which is applied to near field concepts described in Section 6.1.1. Its features are as follows:

- Rocks containing major heterogeneities, in particular highly permeable structures, can be deterministically expressed, although this option was not used. Instead, the large number of faults and fractures are stochastically represented, while engineered structures expressed as homogeneous continuums, to allow the target area to be represented as a 3D hydraulic conductivity tensor field.
- For the constructed tensor field, by imposing representative boundary conditions, saturated groundwater flow analysis is used to calculate the water head distribution and Darcy velocity vector field.
- For the calculated 3D groundwater velocity vector field and using a random walk method, advection and dispersion in fractures, matrix diffusion and solute dispersion and sorption could be simulated. However, in this application, sorption was not considered.

Here, information on fracture networks from SDMs (Section 3.3.3) is used to stochastically generate hydraulic conductivity tensor field realisations (using statistical data on distributions of fracture orientations, length distributions, 3D fracture densities, etc.). The hydraulic gradient required for groundwater flow analysis at the near field scale is derived from the head distribution from panel scale analysis, which in turn is based on results of the groundwater flow analysis on the repository scale. This repository scale analysis is the same as that carried out in the design study for the disposal panel layout (see Section 4.5.4), based on rock-specific SDMs to establish an equivalent continuum model that deterministically accounts for major fault zones.

Below, the transport processes specifically considered in Partridge as applied in this report are described.

(a) EBS

For particle tracking, the source term is defined as a unit mass represented by a large number of particles. These particles are considered to diffuse through the EBS, which is represented as a porous medium.

(b) Host rock

As noted in Section 3.3.3, advection in faults and fractures dominates groundwater flow in plutonic and Pre-Neogene sediments, allowing a DFN model to be applied. Since advection in Neogene sediments can also occur in the rock matrix, a model expressing features of both fracture and porous matrix flow is applied.

The DFN model particle tracking analysis includes solute transport by advection and dispersion in the fractures, with diffusion into the rock matrix. For Neogene sediments, however, the DFN model has to be extended to include advection within the rock matrix, treated as a porous medium, as shown in Figure 6.4-6.

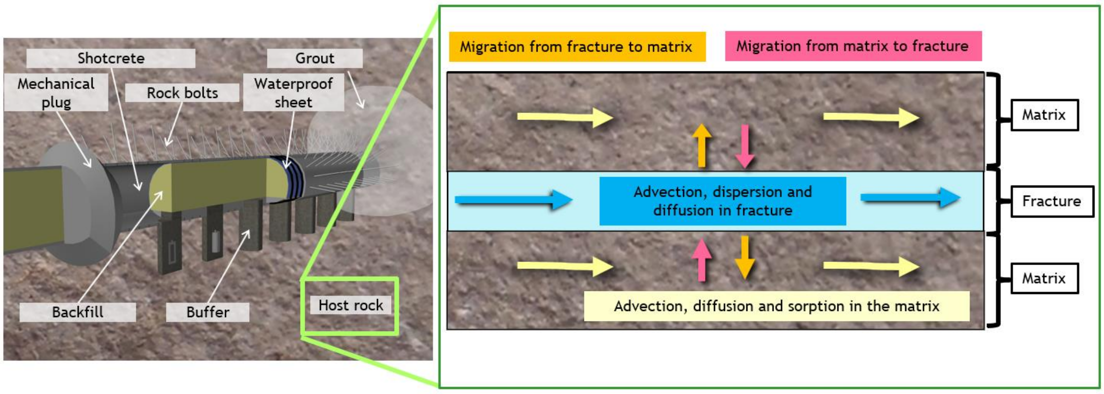


Figure 6.4-6 Conceptual illustration of migration model for fractures and matrix of Neogene sediments (Example of HLW (H12V))

(iv) Development of the simplified RN migration model

Based on the modelling concepts described in 6.4.1 (2) (i) and (ii), the process of constructing a simplified RN migration model for the near field scale using Partridge is illustrated in Figure 6.4-7. The model is similar to the one used for the H12 study, apart from the way channels are identified by particle tracks in the 3D DFN model. As noted earlier, this modelling approach will be further developed in coming assessments.

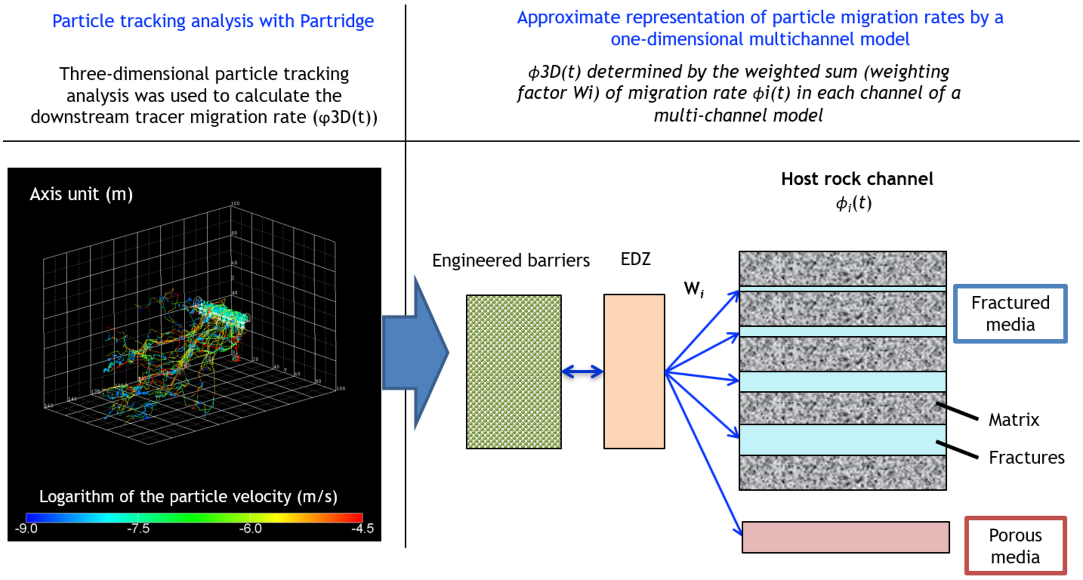


Figure 6.4-7 Construction of a simplified RN migration model for the near field

After generating a DFN model from each SDM, Partridge is used to carry out groundwater flow analysis and particle tracking in the calculated hydraulic field. The groundwater flow paths in the host rock are then simulated by a set of one-dimensional parallel plate fractures in a simplified model (multi-channel model) to allow simulation by the analysis code Goldsim © [67]. The time-dependent migration of particles released from the entire near field is obtained by 3D particle tracking analysis. This release curve is simulated by a set of one-dimensional channels of different transmissivity (Ti) and the weighting value (W_i). These parameters are selected such that the weighted sum of the breakthrough of a unit release for each channel sufficiently well match the calculated release curve, see Figure 6.4-12. The Ti of each channel of the multi-channel model is based on the distribution of the hydraulic conductivity with respect to host rock fractures, where the upper and lower limits given to the channel are used as optimisation variables. Solute release from the EBS is captured by a mixing tank model of the EDZ, with weighting of distribution to each channel given by W_i values (Section 6.4.1 (2) (iv) (e)).

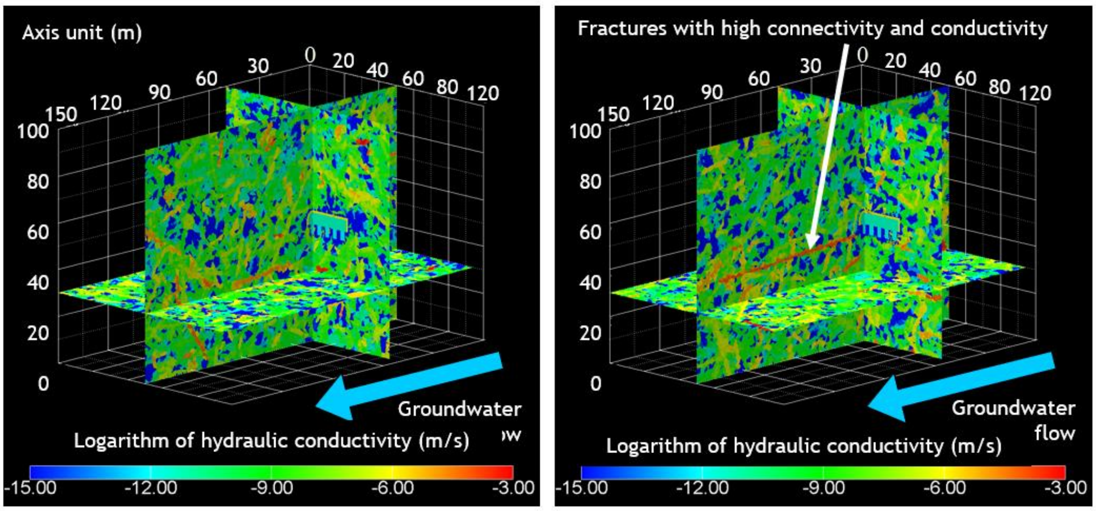
In H12 [3], the W_i channel weighting was defined on the basis of hydraulic conductivity distributions of fractures in the host rock (log-normal distribution), which is an oversimplification in terms of determining the migration rate of RNs. To more realistically represent the solute transport characteristics of the DFN in this report, the W_i was derived instead from the 3D Partridge simulations.

As mentioned in Section 6.4.1 (2) (iii) (b), in addition to advective flow in DFNs for plutonic or Pre-Neogene sediments, advection-dispersion processes in the rock matrix (Figure 6.4-5) have to be considered for Neogene sediments. For this case the advection-dispersion processes in the rock matrix option were used in the 3D Partridge simulations.

The simplified RN migration analysis model for the host rock and EBS at a near field scale, depending on the host rock involved, is described further below.

(a) The DFN model

Since the spatial distribution of fractures is statistically treated, the computed distribution of fractures in each realisation does not produce the same flow field. As an example, Figure 6.4-8 shows the finite elements of the groundwater flow model generated by Partridge for plutonic rock (see Section 3.3.3), with the two different realisations showing the assigned hydraulic conductivities.



(a) (b)

Figure 6.4-8 Examples of hydraulic conductivity distributions of finite elements for two different realisations of groundwater flow models

Comparing realisations (a) and (b), the impact of large fractures with high connectivity and hydraulic conductivity lying parallel to the main groundwater flow direction is highlighted in the latter. It can be expected that such features will have a large influence on RN migration and hence, when conducting the safety assessment, it is necessary to pay attention to how to determine representative groundwater flow and RN transfer behaviour, taking into consideration the statistical range involved.

One way to deal with statistical variability is to create as many realisations as possible and conduct groundwater flow and particle track analysis for each of them. In general, however, it takes a long computation time for particle tracking analysis in such a 3D DFN model, so the practical number of such analyses is limited.

Therefore, in this report, groundwater flow analysis, which has shorter calculation times than particle tracking analysis, is performed for many realisations. Based on groundwater travel time and migration path length to the downstream boundary, decision on the DFN models to be used for particle tracking analysis to capture the diversity of the generated fields is made, using the obtained hydraulic conductivity as an indicator. Specifically, 100 DFN realisations were created for groundwater flow analysis and the average hydraulic conductivity of the modelled rock volume with respect to the main flow direction of groundwater was evaluated. Then, these 100 realisations were broken down into 5 groups, each covering the results of 10 realisations, in order to select the realisations used for particle tracking analysis (see Figure 6.4-9). For each group, 2 realisations were sampled.

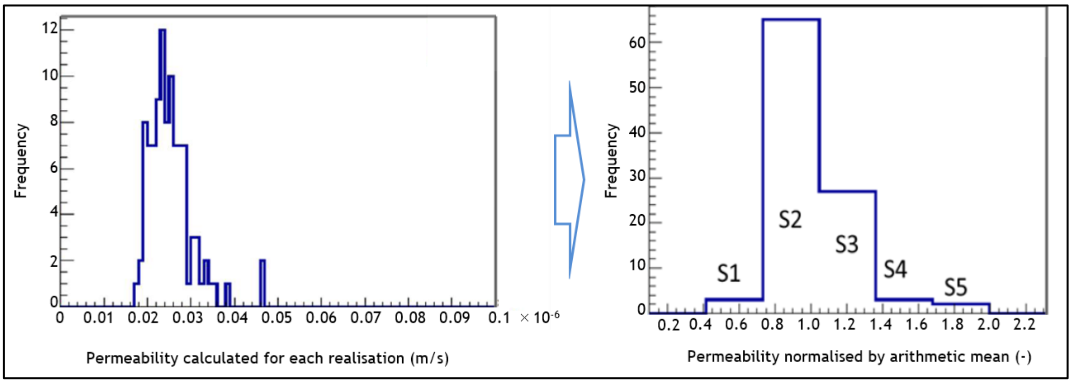


Figure 6.4-9 Stratified sampling based on 100 realisations

These results are multiplied by a weighting for each group, obtained from the frequency distribution, to obtain the average value. This allows particle tracking analysis to generate solute transport characteristics with a relatively small number of realisations. Details of this approach and a discussion of its validity are given in Supporting Report 6-14.

Even for actual sites, initial fracture information is obtained by relatively limited borehole surveys and hence fracture networks of the entire repository will be statistically generated and evaluated. Thus, taking into consideration practical computing restrictions, it is necessary to determine what would be a sufficient number of realisations to properly evaluate a site in a stepwise manner.

Even if the number of realisations as described above is reduced, for each realisation, using the functions of the Partridge code (see 6.4.1 (2) (iii)) for both the EBS and the 3D analysis of transport processes in the host rock still requires a great deal of computation time. For this reason, according to the method described in (b) to (e) below, the calculation load for each realisation was reduced.

(b) Particle tracking analysis using Partridge

First of all, for the analysed system of the HLW EBS (H12V) mentioned in Section 6.4.1 (2) (ii) above, a 3D groundwater flow analysis was carried out assuming a homogeneous equivalent porous medium model. The information on the pressure head at each node of the finite elements obtained here was taken over to the DFN model and the actual flow velocity in the fracture and rock matrix was calculated. Then, based on the diffusion coefficients of the EBS and host rock, non-sorbing particle tracking analysis in three dimensions, for an instant release of "tracer" from waste and without considering decay was performed. Here parameters used for 3D analysis of the groundwater flow are, as discussed in Section 6.4.1 (1), for repository layout studies on a 10 km x 10 km scale (details are summarised in Supporting Report 6-14).

In the particle tracking analysis, the tracer breakthrough to the downstream side of the region depends on the shape/transport characteristics of the EBS and the heterogeneous fracture network of the surrounding host rock, and on the location of the downstream boundary. The analysis results in a "basic solution" on the transport rate of solute, without taking into consideration elution behaviour, solubility, sorption and decay. These processes, which would depend on the source term and different migration properties of different RNs, could then be modelled for the set of 1D channels obtained from the 3D particle tracking analysis.

For H12V, 2 realisations were randomly extracted from each hydraulic conductivity group (S1 to S5) shown in Figure 6.4-9, to give a total of 10 simulations of tracer migration to the model downstream exit. A weighted average, also shown in the figure (solid line) was obtained by applying the weights of the permeability group representing each individual breakthrough curve. The tracer release curves from the near field, normalised by the initial number of particles released at time zero, is shown in Figure 6.4-10.

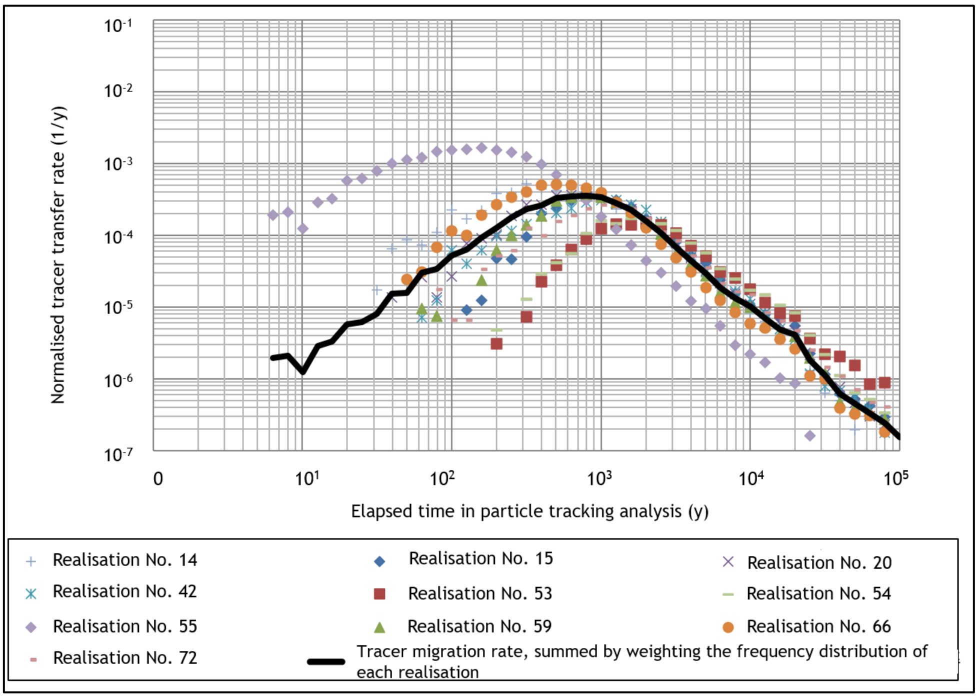


Figure 6.4-10 Calculated average tracer migration (solid line) for HLW (H12V) based on particle tracking analysis for 10 realisations (see Supporting Report 6-14 for details on each realisation)

The figure shows dispersion effects due to advection in the heterogeneous fissure network, with the results used to construct a one-dimensional multi-channel model for the host rock, as described in (d) below. A similar procedure was applied for the other rock types and for the TRU repository.

(c) Simplified RN migration model for the EBS

To model the EBS for HLW and TRU waste, simplifications are introduced to the base scenario to capture specific designs without considering the associated host rock.

(A) HLW

Figure 6.4-11 shows the simplified one-dimensional coupled box model of EBS RN release and migration for HLW. In the migration processes shown in the figure, radioactive decay/ingrowth is taken into consideration.

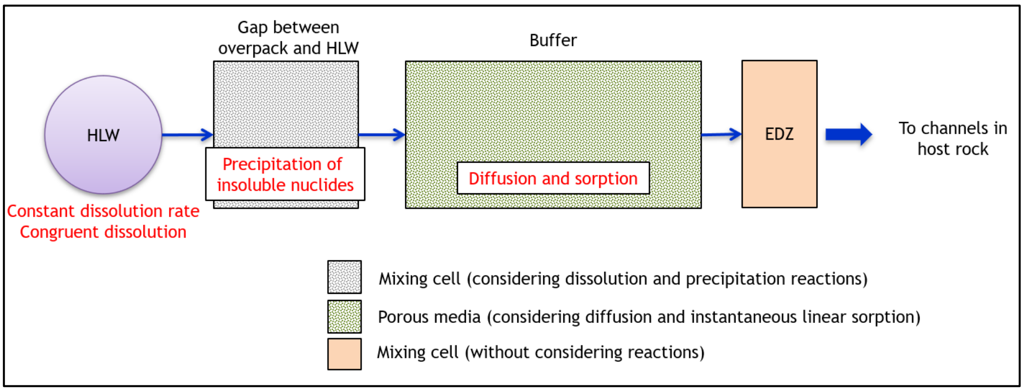


Figure 6.4-11 Concept of simplified RN release and transport model for the HLW EBS

After the overpack loses the function of containment, the vitrified HLW contacts groundwater and dissolves at a defined rate. RNs are uniformly distributed within the glass and are considered to dissolve congruently with the glass matrix. Although, initially, the glass dissolution rate is related to the local dissolved silica concentration, this reaches saturation after which the dissolution rate is constant. RN concentrations in pore fluid within the overpack may be limited by elemental solubility (assuming thermodynamic equilibrium); if this is exceeded, precipitation (and, possibly, co-precipitation) occurs. Since colloids are filtered out by the buffer, as long as its safety functions are upheld, RN partitioning between water and colloids need not be modelled. For RN migration analysis, solubility limits are not specified for elements that are expected to be highly soluble (e.g., Cl, Cs, I). For elements with multiple isotopes, solubility concentration limits are shared between them, according to their relative abundance. Here, unlike H12, the impact of stable isotopes was conservatively ignored due to uncertainty in the concentration of these, although this may be revisited in the future. Radioactive decay and ingrowth are also modelled in the mixing tank.

Dissolved RNs in the overpack mixing tank are assumed to diffuse through the buffer material, with a concentration gradient set by the concentration in the source and EDZ mixing tanks, while being retarded by sorption and attenuated by radioactive decay. Dissolution and precipitation are not modelled in the buffer, since RN concentrations are higher at the source term end. It is conservatively assumed that the RNs released from the buffer mix instantaneously with groundwater within the EDZ, in turn forming the source term for transport through the host rock. The EDZ mixing tank releases RNs to multiple one-dimensional channels representing the host rock, based on the defined W_i (see (e) below). The migration path was simplified, while maintaining conservatism, by not considering the backfilled part of the emplacement tunnel and the access tunnels. However, for the hypothetical case that the function of the backfill was lost, this simplification means that the current assessment would not allow the analysis to distinguish between different EBS designs of the tunnel backfill.

For the PEM, no safety function is assigned to the steel handling shell and thus the release model from the EBS is the same as for H12V. This implies that the difference in flow geometry, where the EDZ for the PEM is around the deposition tunnel and where there is diffusion from buffer through the backfill, is ignored. Furthermore, it is assumed that the corrosion of the handling shell does not have any impact on the buffer. While these simplifications can be conservatively justified, they also mean that the current assessment does not allow the analysis to distinguish between H12V and the PEM options, which will be a goal for future model improvements.

(B) TRU waste

Figure 6.4-12 shows the concept of a simplified one-dimensional coupled box model of EBS RN release and migration for TRU waste. As for HLW, in the migration processes shown in the figure, radioactive decay/ingrowth is taken into consideration. For waste package A, the delay in the release due to the saturation time and containment time of the waste containers are conservatively ignored, whereas the containment time for waste package B is included in the analysis.

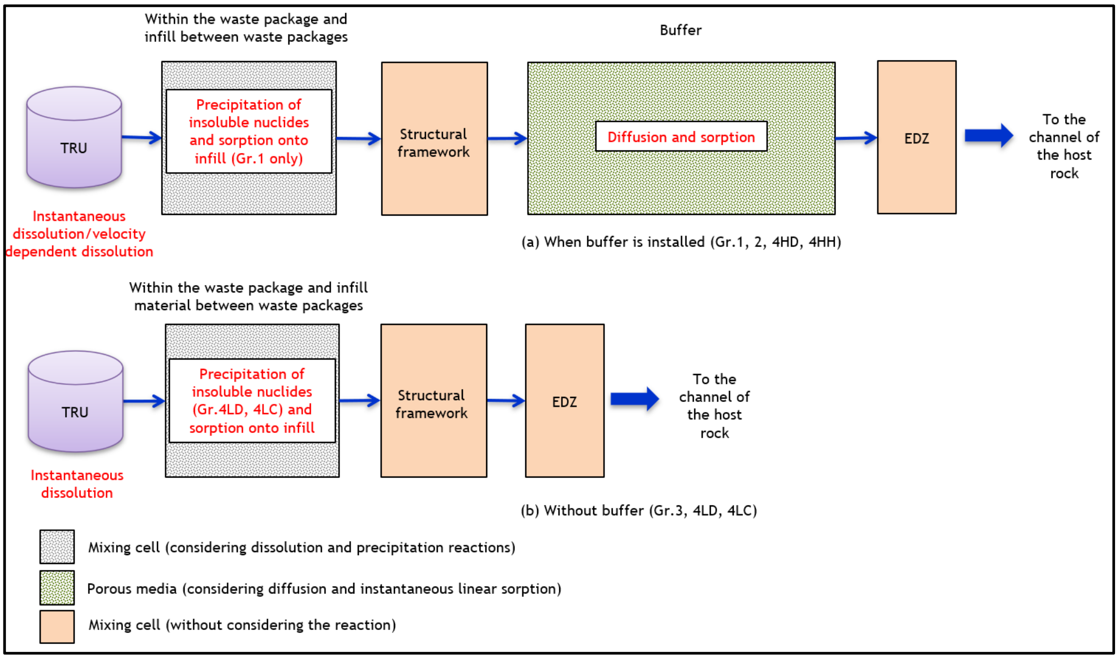


Figure 6.4-12 Concept of simplified RN release and transport models for TRU EBS

RNs present in the metal waste contained in Gr.2 are released congruently with metal corrosion: the other Gr.2 materials and waste in other groups are assumed to release contained RNs instantly into surrounding porewater.

Released RNs are assumed to be sorbed on the EBS waste packaging and infill materials, which are treated together as a mixing tank. However, as discussed in Section 6.3, for Grs.2 and 4H, which are heat-emitting, it was conservatively assumed that cement hydrate will be thermally altered and sorption onto it is not considered. Furthermore, as also discussed in Section 6.3, Gr.3 includes a large amount of nitrate which also is assumed to affect sorption. In all cases, porewater RN concentrations are assumed to be constrained by elemental solubilities – treated in exactly the same way as for HLW, while considering the impact of the ambient hyperalkaline conditions.

In the case of Grs.1, 2 and 4H, RN transport within the EBS is predominantly by diffusion, while additional sorption and radioactive decay occurs within the buffer. For Grs.3 and 4L, RNs from the EBS mixing tank pass directly to the EDZ by advective flow. The effect of decay/ingrowth during transport processes is taken into account and the treatment of releases from the EDZ mixing tank into the multiple channels of the host rock is the same as for the HLW case.

In modelling the RN migration from the EBS, in both HLW and TRU waste cases, supporting engineered structures that are not assigned safety functions are not considered.

(d) RN migration model for a simplified host rock

As mentioned in (b) above, tracer migration rates obtained by 3D transport analysis are used to condition a model in which the host rock is represented by one-dimensional parallel plates with different hydraulic conductivities. This greatly increases the efficiency of calculation of the various analysis cases for safety assessment scenarios. The validity of such simplification is discussed in a NUMO technical report [23].

Section 6.4.1 (2) (iii) (b) noted that, for plutonic rocks and Pre-Neogene sediments, a multi-channel model of advection-dispersion in one-dimensional parallel plate fractures can simulate RN migration processes including decay chains and diffusion into and sorption onto the rock matrix. The situation is generally similar for Neogene sediments but, in addition to advection in fractures, advection-dispersion in the rock matrix, considered as a porous medium, has also to be handled as discussed in section 6.4.1 (2) (iv).

(e) Approximation of Partridge results by the simplified model

A simplified near field model is constructed in which the one-dimensional radial migration analysis model of the EBS mentioned in (c) and the multi-channel model of host rock described in (d) are combined, with the EDZ handled by a mixing tank model. The hydraulic conductivity of each channel (Ti) is used to derive a normalised particle flux (φi(t)) from the EDZ, which is then integrated using the W_i to derive a total release flux (φ3D(t)) as shown in Figure 6.4-13 for the example of H12V in plutonic rock.

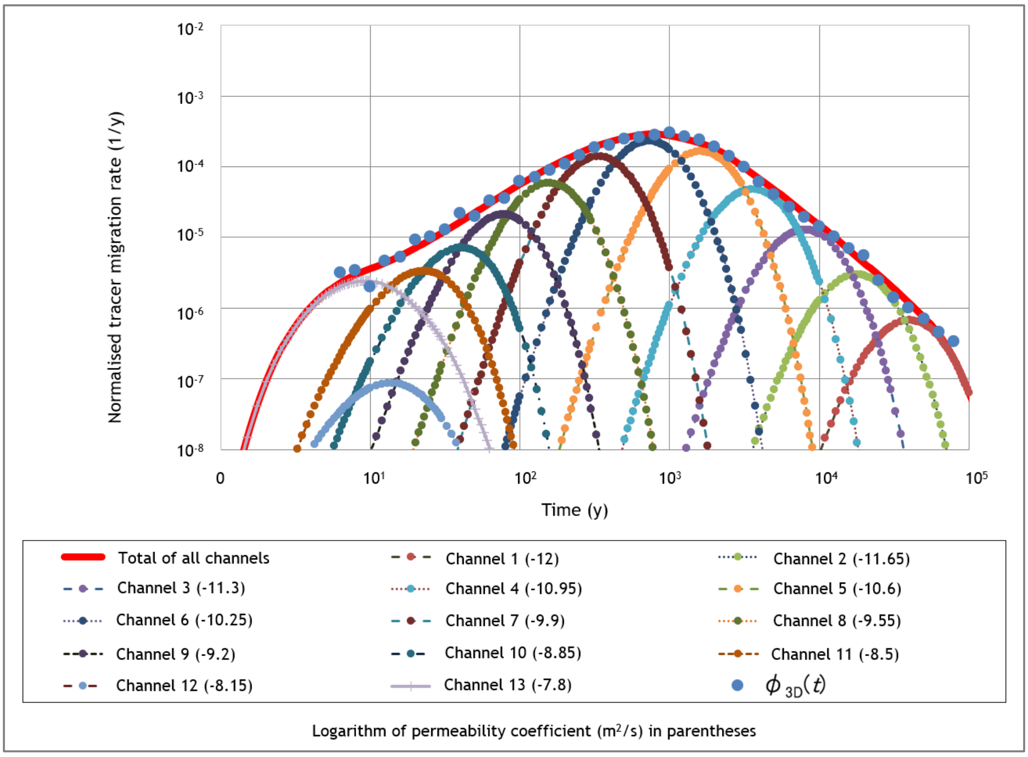


Figure 6.4-13 Approximation using the one-dimensional multi-channel model to match the combination of a set of channels (red line) with the average tracer migration rate (the solid line in Figure 6.4-10, here represented by blue dots) obtained by 3D particle tracking analysis (H12V plutonic rock case)

The figure shows how the calculated 3D release curve was simulated by the multi-channel model, as explained in section 6.4.1 (2) (iv) and Figure 6.4-7 above. The length of each channel is 100 m. At first the fitting was made with 41 channels, but it was found that it was possible to adequately simulate tracer migration using only 13 channels. Given the allocated W_i of the RN flowing into each channel, RN migration processes described in (c) and (d) above were analysed using the code GoldSim ©.

Neogene sediments were simulated by combining the DFN model with a porous medium model and assessing flow using particle tracking. In the multi-channel model, porous flow was represented by one of the channels, but it was concluded that this did not contribute significantly as a RN migration pathway (Supporting Report 6-13).

(v) Datasets for near field scale migration

Based on the above simplified RN release and migration model, required parameters were set for the associated analysis cases as described below.

(a) THMC data

(A) Thermal data

As discussed in Section 6.3.2 (3) (i), for both HLW and TRU waste, the repository takes time to re-saturate, after which contact between waste and water is restricted due to containment by the overpacks or waste packages for a certain period of time: only thereafter does elution of RNs commence. Based on the results of thermal analysis for buffer in the different repository designs (see Supporting Reports 4-39, 4-40, 4-41), the entire near field has returned to the original rock ambient temperature when RNs are released – so this temperature is used to set relevant RN migration parameters, apart from conservatively discarding sorption in the potentially degraded cement hydrate for TRU Grs.2 and 4H, as described previously

The rock ambient temperature was set at 45 °C for plutonic rocks and Pre-Neogene sediments (disposal depth 1,000 m) and 30 °C for Neogene sediments (disposal depth 500 m) (see Section 3.3.3 (6) (ii)).

(B) Mechanical properties

After the repository is closed, the density of the buffer may change, due to overpack corrosion, structural framework settlement, etc., but it is designed so that the required density is kept for a long time after closure, maintaining the swelling pressure developed after re-saturation. Thus, the influence of any change of mechanical properties when setting RN migration parameters was not considered.

(C) Hydraulic properties

For all repositories and host rocks considered, backfilling material and cementitious support structures that are not part of the EBS will alter with time after closure and hence are conservatively assigned high hydraulic conductivity values.

- Hydraulic gradient

Basically, it is assumed that the initial hydraulic gradient of the SDM recovers quickly after any perturbations due to construction and operation and is then maintained constant for the entire calculation period. Long-term changes of the geological environment are not considered, as explained in Section 6.3.

From the results of the groundwater flow analysis (Supporting Report 4-49) at a repository scale, the gradient is set as 0.05 in the case of plutonic rocks and Pre-Neogene sediments; for Neogene sediments it is set as 0.06 (Supporting Report 6-14).

- Hydraulic conductivity of buffer

In the setting of the buffer hydraulic conductivity, potential impacts of long-term degeneration as a result of interaction with any concrete present were taken into consideration. Degradation due to future changes in groundwater chemistry was not considered.

For H12V, no cementitious material is assumed to contact the buffer for any host rock, therefore there is no change in hydraulic conductivity due to alteration and the design hydraulic conductivity specification (1.0×10^{-12} m/s) is assumed for the entire assessment period (see Supporting Report 4-15). For the PEM variant, a concrete pedestal is assumed to interact with the buffer (although backfilling material is arranged around the handling shell containing it), so it is assumed that the hydraulic conductivity increases by two orders of magnitude to 1.0×10^{-10} m/s for the entire assessment period. However, this value is still sufficiently low for migration to be diffusion dominated in the buffer.

For TRU waste, a range of concrete structures are laid in contact with any buffer present, so alteration was investigated taking this into consideration. According to the result of the safety evaluations so far, non-sorbing I-129 dominates the dose from TRU waste, but is released from the EBS over a relatively short time period [3][14]. From this point of view, the period during which the buffer material function of suppressing RN migration is important is shorter than the HLW case, while the degree of change in hydraulic conductivity due to alteration would be relatively small. Thus, for host rocks in which the amount of cementitious material in contact with the buffer is relatively small (plutonic rocks and Pre-Neogene sediments), the design hydraulic conductivity specification of 1.0 x 10^{-12} m/s is assumed. For the Neogene sediments, although the quantity of cementitious materials in contact with the buffer is larger, the period of alteration is shorter than that for HLW and thus the hydraulic conductivity was assumed to increase by one order of magnitude to 1.0 x 10^{-11} m/s. However, again, these values are still sufficiently low for migration to be diffusion dominated in the buffer.

- Hydraulic conductivity of cementitious materials

TRU wastes, other than Gr.2, are conditioned with cementitious materials. In addition, packaging and infilling of all waste groups involves cementitious material and the structural frameworks are predominantly constructed from concrete. Buffer layers surround the disposal tunnels of Grs.1, 2, 4H and inside these solute transport through cementitious materials is dominated by diffusion. This will be the case even though cracking of infill is considered likely to occur and integrity of structural frameworks cannot be assured (see Supporting Report 4-35). As it has little impact on performance, the hydraulic conductivity of the entire EBS region within the bentonite is conservatively set equivalent to that of sand (1.0 x 10^{-5} m/s) [68].

For Grs.3 and 4L, without buffer, advective flow occurs, which is dependent on the hydraulic conductivity of the EBS. As above, it is impossible to preclude cracking after construction. Based on core data from old dams [69], hydraulic conductivity of the structural framework is set at 1.0 x 10^{-7} m/s for 200 y after closure, and 1.0 x 10^{-5} m/s, equivalent to that of sand, thereafter; the same as for waste package and vault infill (Supporting Report 6-16).

- EDZ hydraulic conditions

In the mixing cell model of the EDZ, to calculate the RN concentrations therein, the groundwater flow rate through it and its thickness is required. Porosity is conservatively set to 1. For the HLW repository, based on based on expert knowledge, the H12V disposal tunnel is assumed to be excavated by the drill and blast method, producing an EDZ with a of thickness of 1.0 m and a hydraulic conductivity of 100 times that of the host rock. For the PEM, an EDZ of thickness of 0.5 m resulting from excavation by TBM is assumed, with hydraulic conductivity again 100 times that of the host rock (see Supporting Reports 4-44, 4-67). The TRU waste disposal vault EDZ was set similar to that of the disposal tunnel for HLW.

Groundwater flow rate through the EDZ used for RN migration analysis was calculated from the hydraulic conductivity of the EDZ and permeabilities of undisturbed rock and the EBS (taken as that of buffer, except for TRU waste Grs.3 and 4L where the value for backfill was used). The hydraulic conductivity and hydraulic gradient of the rock were determined using the theoretical solution of groundwater flow presented in the TRU-2 report [14], as described in more detail in Supporting Report 6-13.

- Hydraulic conductivity of host rock

The hydraulic characteristics of the one-dimensional multi-channel model were derived by the methods already described in Section 6.4.1 (2) (iv). The hydraulic conductivity of the near field rock could thus be represented by the modelled set of fracture channels, with their respective transmissivity values (Ti.) The width of each channel was set in a similar way to that in the H12 report, and was calculated from Ti using empirical rules. For Neogene sediments, the channel representing the porous medium between fractures was given the hydraulic conductivity of the matrix provided in Section 3.3.3 (4) (ii) (b).

(D) Chemistry

- Groundwater chemistry in host rocks

The groundwater chemistries of host rocks, as specified in Chapter 3 (Table 3.3-16), are assumed to be constant over the entire assessment period. Long-term changes of the geological environment are not considered in this assessment, as explained in Section 6.3.

- Water chemistry in the EBS

For HLW, it is necessary to model the chemistry of the buffer porewater in order to derive sorption distribution coefficients and effective diffusion coefficients in this material. In addition, in order to determine the solubility of RNs within the overpack, it is necessary to set the water chemistry therein. Solubilities of RNs are derived from thermodynamic calculations, for porewater chemistry in the HLW buffer and the TRU mortar infilling material. Although the strict applicability of this approach to a microporous medium like compacted bentonite is debatable [20], this is used here to assess ion exchange reactions of montmorillonite, acid-base reactions of surface hydroxyl groups, dissolution and precipitation reactions of accompanying minerals and reactions of iron corrosion products. Based on mass balance arguments, the Na-bentonite will persist for a long time, assuring relatively constant water chemistry in contact with the failed overpack, where it can be considered that elemental solubilities are set (colloids may be released from corroding glass and migrate through the fractured overpack, but are completely immobile in compacted bentonite).

It should be noted that the backfill includes the same bentonite material as the buffer, mixed with excavated rock, so no significant additional changes of groundwater composition are assumed to occur (Section 4.5.3 (1)) and hence this is not considered in setting the water composition of the EBS.

The simplified TRU waste EBS models in Section 6.4.1 (2) (iv) (c) distinguish between waste groups with (1, 2 and 4H) and without (3 and 4L) external buffer and these are assigned different porewater chemistries. For the former case, TRU waste buffer porewater chemistry was taken to be the same as in the HLW case. As explained in Supporting Report 6-15, the alteration of bentonite is negligible and the specification of the buffer for HLW and TRU are almost the same, while the thickness of the TRU buffer is larger than that for HLW. Porewater chemistry of the infill ("infill porewater") inside this buffer was modelled by considering reaction of buffer porewater with this cementitious material, assuming thermodynamic equilibrium with evolving solid phases. Initially porewater in cementitious material is characterised as "Region I" with pH = 13 or more due to elution of sodium and potassium hydroxides. Later, in "Region II", equilibrium with portlandite buffers porewater pH to about 12.5. After that, in Region III, a range of calcium silicate hydrate phases control pH, which drops below 12.5 [70]. Coupled reaction/solute transport modelling of cement/buffer interaction suggests that portlandite in the infill remains over the modelled timescale (Supporting Report 6-8). Thus, infill porewater chemistry was set for Regions I and II, using a method developed by JAEA [71]. It is noted that this model approach includes many simplifications, since many key solids are only metastable and the assumption of a mixing tank would not properly describe the much slower diffusive transport inside the EBS. These simplifications need to be revisited in future safety cases.

For TRU waste without buffer, groundwater reacts directly with cementitious infill, which has a relatively high hydraulic conductivity (Section 6.3.2 (3) (i)) and, together with concrete structures, provides a large inventory of reactive material (Supporting Report 6-15). Again, for this case, coupled reaction/solute transport modelling of cement/groundwater interaction suggests that infill porewater remains in Regions I and II (Supporting Report 6-8) over the modelled timescale.

Geochemical calculation code PHREEQC ver.3 [72] and thermodynamic database JAEA β-TDB v 1.07 [73] were used for the analysis of equilibrium reactions.

For TRU waste Gr.3 (without buffer), porewater chemistry in the EBS is also impacted by dissolution of the nitrate contained in the waste, which could yield high ionic strengths of up to about 8 mol/l (see Supporting Report 6-8), since it is conservatively assumed that the nitrate contained in the bitumen is immediately dissolved, regardless of the speed of degradation of the bitumen. However, the thermodynamic models/databases used do not allow activity corrections required for such high ionic strength and hence this impact on porewater chemistry was not included directly, but its influence on RN migration parameters is taken into account, as described in (b) below.

Appendix Tables 5 to 8 present the model EBS porewater chemistries, which are described in more detail in Supporting Report 6-15.

(b) RN migration parameters

(A) Parameters related to waste

- RN release time and RN inventory

As noted previously, it is conservatively assumed that the HLW overpack will maintain its containment function for at least 1 ky, even if the containment might actually be at least 10 times longer. However, as explained in Section 6.3.2 (3) (i), it is also very conservatively assumed in the analysis that all 40,000 overpacks fail simultaneously 1 ky after repository closure and RN release begins at this time. The radioactivity inventory of HLW at time of emplacement is given in Table 6.1-3, so the impacts of decay between then and the failure time of the overpack is calculated.

The TRU waste package A is not assigned a containment function (see Section 6.3.2 (3) (i)), since there is no upper lid on these waste packages. However, as discussed in Section 4.4.2 (2) (v) (a), it may still take some time before releases from the waste would start. In order to address the uncertainty associated with estimating this time, it is, as in the TRU-2 report, conservatively assumed that release of RNs starts immediately after repository closure.

Waste package B is designed to contribute to the safety function “prevention of contact between waste and groundwater” for a limited time. As described in Section 4.4.2 (2) (v) (b), even considering the possibility of local corrosion and the influence of radiolysis, the assumed corrosion depth is less than 10 mm in 300 y. Since the waste package container is 50 mm thick, it is considered corrosive failure will not occur within this time. As further discussed in Section 4.4.2 (2) (v) (b), the structural integrity of the waste package is also considered due to the impact of the hydrostatic pressure after re-saturation and the reduced wall thickness. Even so, structural integrity is considered to be maintained. From this, it is assumed likely to prevent contact between groundwater and waste for at least 300 y, and this is set as the initiation time for releases in the assessment.

The radioactivity inventory of TRU waste at the time of emplacement is given in Table 6.1-4, which is the assumed start of elution of RNs in the case of waste package A. In the case of the waste package B, these inventories have to be corrected for 300 y of decay (see Supporting Report 2-3).

- RN dissolution rate

For HLW, RNs are released congruently with glass dissolution, which proceeds at a long-term rate (after silica saturation) as given in the H12 report. Here, corrections were made to the glass dissolution rates obtained in long-term leaching tests to account for the temperature of the repository and the surface area increase due to cracking during manufacture of the glass. The uncertainties in the glass dissolution rate are briefly discussed in Supporting Report 6-9. The period required for total dissolution of the glass is conservatively estimated to be about 70 ky, and this value is assumed to apply in this report.

For TRU waste, as in TRU-2, conditioning matrices for Grs.1, 3 and 4 are conservatively assumed to be instantaneously soluble in EBS porewater (Section 6.3.3 (1)), with the RN inventory being well mixed within this volume, disregarding the potential diffusive migration within the degrading waste form. For Gr.2, RNs adhering to the surface of hulls and end pieces are treated similarly, while those incorporated into metals are released congruently with their corrosion. In line with TRU-2, corrosion lifetimes for the metals involved are specified (zircaloy: 11.4 ky, stainless steel: 8.5 ky), allowing elution rates of RNs to be set assuming that the material corrodes at a constant rate.

(B) Parameters related to the EBS

- Solubility

Nuclide solubilities are considered as constraints for HLW and TRU waste Grs.1, 2, 4L and 4H (Section 6.4.1 (2) (iv) (c)).

For HLW, thermodynamic equilibrium calculations, using the EBS porewater chemistry specified in Section 6.4.1 (2) (v) (a) and data on minerals with the potential to precipitate, forms the basis of selecting assumed solubility-limiting solid phases [4] for each RN. Next, solubility is calculated using thermodynamic calculations assuming that porewater and the solubility-limited solid phase are in equilibrium. In cases of uncertainty in the stability of solid phases, it was decided to select simple solids that are known to exist under relevant geological environmental conditions, see Supporting Report 6-17.

For TRU waste Grs.1, 2, 4L and 4H, basically the same procedure is adopted; but, as discussed in Section 6.4.1(2) (v) (a), EBS porewater chemistry evolves with time following reaction between the buffer and the cementitious material. The solubility was calculated for the different porewater chemistries involved and the highest value was selected for the calculational database. The effect of iso-saccharine acid, originating from degradation of organic matter in TRU Waste Gr.2, is included in the thermodynamic equilibrium calculation.

For the calculation of the solubility, the calculation code PHREEQC Ver.3 [72] and database JAEA-TDB 140331S0.Tdb [74] were used, with partial modifications of data for U and Zr (see Supporting Report 6-17). Although the set value of the ambient rock temperature is 30 °C (Neogene sediments) or 45 °C (plutonic rocks and Pre-Neogene sediments), solubility is calculated at 25 °C, for which most thermodynamic data are specified. Although the influence of small temperature changes on solubility were shown not to be significant in the H12 report or for SR-Site [44], due to the uncertainty [75] involved, increased solubility due to temperature was studied in variant scenarios.

For TRU waste Gr.3, thermodynamic equilibrium calculations cannot be applied as porewater chemistry is not set (see 6.4.1 (2) (v) (a) 4) and hence solubility limits are conservatively not specified (see Supporting Report 6-17). Therefore, from the viewpoint of ensuring traceability in safety evaluation, it is assumed that the entire RN inventory is instantaneously dissolved in the EBS porewater.

Appendix Tables 9 to 11 summarise solubilities used for HLW and TRU waste RN migration analysis, with more information on the solubility setting process in Supporting Report 6-17.

- Effective diffusion coefficient

Effective diffusion coefficients of elements in buffer are selected based on a method developed during joint research between NUMO and JAEA [76], as shown in Figure 6.4-14. The analysis considers the effects of porewater ionic strength and the dry density of the buffer. This treatment is judged sufficient at the present time, although it is understood that Fickian diffusion is not strictly applicable to compacted bentonite, considering its microporous, semi-permeable membrane structure.

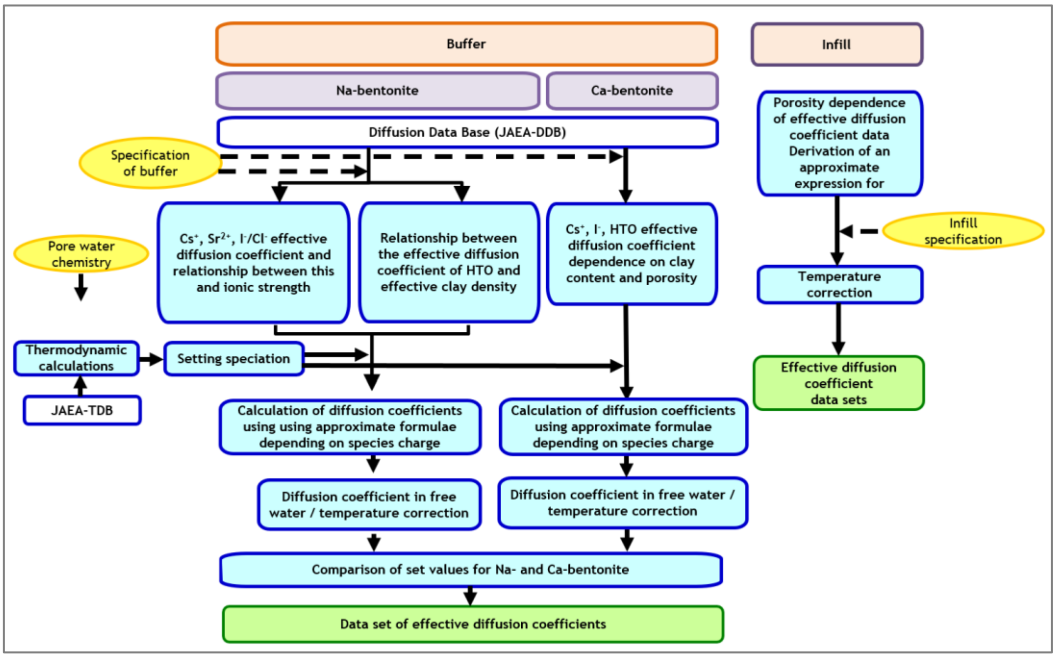


Figure 6.4-14 Procedure for setting effective diffusion coefficients for buffer and cementitious material

From the groundwater chemistry defined for the three representative host rocks, it is expected that bentonite in the buffer will remain Na-type for a long period of time, while reaction between groundwater and leachate from cementitious material causing alteration to Ca-type is considered (see Supporting Report 6-15): for each of these effective diffusion coefficients are given.

With respect to the effective diffusion coefficients of elements in Na-type bentonite, the JAEA-DDB [77] was used to select effective diffusion coefficients for Cs^{+}, Sr^{2+}, I^{-}/ Cl^{-} for the given specifications of buffer materials (dry density, quartz sand mixing ratio, etc.), together with the ionic strength dependency of diffusivity (Supporting Report 6-19) as determined from effective diffusion coefficients of tritium. The speciation of relevant elements in buffer porewater and their solubility limits were calculated assuming thermodynamic equilibrium at 25 °C (See Section 6.4.1 (2) (v) (b) 2.), using the thermodynamic database JAEA-TDB 140331S0.Tdb [74] with data partially modified for U and Zr (see Supporting Report 6-17). Effective diffusion coefficients are set based on the charge of the predominant aqueous species (Supporting Report 6-18), using the greater abundance of data for $Cs^{+}$and Sr^{2+}; I^{-}/ Cl^{-} and HTO to define reference values for cations, anions and neutral species respectively. Furthermore, temperature corrections for the reference elements, and corrections based on the diffusion coefficients in free water for actual and reference species, are applied. Here, the reliability of thermodynamic data for Pa is noted to be inferior to other elements, giving a large uncertainty in the calculated chemical species in porewater and hence, for this element, the largest among the effective diffusion coefficients of other elements was used. The same process was also applied to data for Ca-type bentonite.

Effective diffusion coefficients of each element were determined for both Na-type and Ca-type bentonite as above, but uncertainties concerning the alteration from Na-type to Ca-type are large and it is difficult to determine the temporal evolution process quantitatively. For the RN migration analysis, therefore, it was conservatively decided to apply the larger values for the effective diffusion coefficient for each element between the two bentonite forms.

Regarding the effective diffusion coefficients of RNs in TRU waste infill or in concrete structural materials, a single value was set for all elements, based on a limited data set for concrete equivalent to vault infill, which assessed both impacts of porosity and temperature [78]. For the reference porosity of 21%, effective diffusivities were set for 30 and 45°C, for disposal at 500 and 1000 m, respectively.

Based on chemical and material properties presented in Supporting Reports 6-15 to 6-17, the process of deriving effective diffusion coefficients of the RNs of interest for HLW and TRU waste are given in Supporting Report 6-19.

- Sorption distribution coefficients

NUMO and JAEA also collaborated in determining elemental sorption data for buffer [76], using the procedure summarised in Figure 6.4-15. Linear, reversible sorption is assumed and taken to be conservative, with nonlinearity handled by selecting sufficiently small sorption coefficients. In terms of sorption distribution coefficients for buffer, sorption data acquired using compressed bentonite of the form emplaced in the repository is limited [79][80], with most experimental work carried out using bentonite suspensions. In terms of such sorption data, there are conflicting views on its inapplicability to compacted bentonite (e.g. [79], [80]). Thus, in this report, values of the sorption distribution coefficient are set based on diffusion data determined for compacted bentonite.

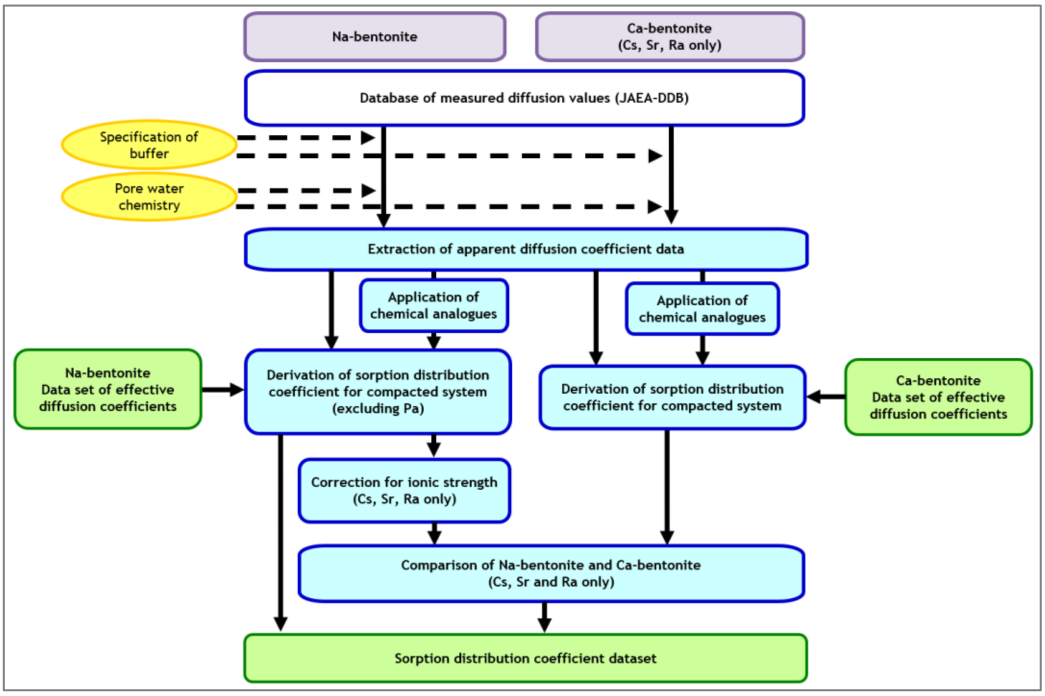


Figure 6.4-15 Procedure for setting elemental sorption distribution coefficients for buffer

Targeting the specified buffer material for HLW and TRU waste (Section 6.4.1 (2) (v) (a)), apparent diffusion coefficients for compacted Na-bentonite measured under test conditions compatible with expected porewater chemistry were extracted from the JAEA-DDB [77]. Combining such data with the effective diffusion coefficients defined above, applicability of Fick's law was assumed to calculate distribution coefficients [81]. For RNs with no reported apparent diffusion coefficients for relevant porewater chemistry, data were derived from elements considered analogous in terms of aqueous speciation.

Due to the complexity of the speciation of Pa and lack of clear analogues in the diffusion coefficients, in this case the distribution coefficients were directly measured using bentonite suspensions.

For elements (e.g. Sr, Cs and Ra) which are considered here to sorb by ion exchange reactions with bentonite interlayer ions, higher sensitivity to ionic strength was expected than for other elements (Supporting Report 6-20). For the high salinity groundwater of Neogene and Pre-Neogene sediments, no relevant apparent diffusion coefficients were available. Therefore, empirical relationships were used to extrapolate measured sorption distribution coefficients to higher salinity – again as described in Supporting Report 6-20. For Ca-bentonite, this approach was limited by the lack of data for Ra, so Sr was used as an analogue. Due to uncertainties in the degree and extent of Ca conversion as a function of time, as for effective diffusivities, distribution coefficients for Na- and Ca-bentonite were derived and the smaller value chosen for the safety assessment calculations.

TRU waste infill specification and porewater chemistry provide the basis for selecting distribution coefficient data: based on uncertainties these are taken from the conservative values [71] in the JAEA-SDB [82], regardless if they represent region I or region II. For Gr.3 nitrate-containing wastes, sorption data are selected conservatively, choosing a value for oxidising conditions if this was lower than for reducing conditions.

Based on chemical and material properties presented in Appendix Tables 15 to 17, the process of deriving distribution coefficients of the elements of interest for HLW and TRU waste are given in Supporting Report 6-20.

(C) Parameters for near field host rock

For the models used, the main parameters influencing RN migration in host rock for all three representative host rock types are classified as those related to solute transport within the channels represented by the one-dimensional multi-channel model and those related to solute transport in the matrix. These were set as follows.

- Parameters related to the channels in near field host rock

• RN migration distance and dispersion length

As described in Section 6.4.1 (2) (iv) (e), the simplified model represents a network of fractures by a set of channels: the migration distance of RNs in each channel is defined to be 100 m. Each channel is characterised by a dispersion length representing the mixing occurring within the channel: the value selected follows the concept in the H12 report, where the dispersion length is set as one tenth of the channel length (100 m), i.e. 10 m.

• Matrix diffusion area

Because of channelling in fractures, not all of the surface of a planar fracture is accessible for diffusion into the surrounding rock matrix (flow-wetted surface), as discussed further for plutonic rocks in Supporting Report 3-29. As a percentage of the total fracture area, flow-wetted surface area has been measured as 40 ~ 50% at the Kamaishi mine [83] and reported by Pyrak-Nolte et al. [84] to lie in the range of 58 to 92%. On this basis, a matrix diffusion area ratio of 50% is selected. However, no account is taken for the fact that, in a heterogeneous fracture, some of the flow will have access by diffusion to low flow or even stagnant areas within the fracture. This may need to be considered in future assessments.

For Neogene sediments, in addition to fracture flow, advection may occur within the altered rock matrix (Supporting Report 3-30) and hence the available matrix area is set to 100%.

For Pre-Neogene sediments, like plutonic rocks, it is considered that the main migration pathways of the groundwater are limited to fractures (see Supporting Report 3-31). Survey results in the Shimanto Belt [85] indicate diffusion into the matrix from 60 to 80% of the fracture surface, as determined from the abundance of openings and fracture infill. The flow wetted surface is conservatively set to 60% for this model.

- Rock matrix parameters

• Matrix diffusion depth

The matrix diffusion depth is set based on the continuity of porosity extending from the fracture into the rock matrix. For plutonic rocks, alteration zones around fractures indicate such connected porosity has a typical depth in the range of 0.01 to 0.1 m and diffusion into the unaltered zone could also be considered (see Supporting Report 3-29). Here it was decided to use a diffusion depth of 0.1 m, as in the H12 report.

For the Neogene sediments, there is no limitation on the range in which diffusion occurs, due to the connected porosity of the entire matrix. Specifically, Supporting Report 3-27 indicates an average fracture separation of 1.6 m, so that half the distance between the fractures is about 0.8 (see Supporting Report 3-30.

For the Pre-Neogene sediments, it is assumed that 10% of fractures are water carrying, corresponding to an average separation of 1 m, so that half the distance between the fractures is about 0.5 m (see Supporting Report 3-28).

• Effective porosity and rock density

From Section 3.3.3 (7) the effective porosity for plutonic rocks, Neogene sediments and Pre-Neogene sediments were set as 0.8%, 25% and 3.5%, respectively. In terms of rock density [86], a value of 2,700 kg/m^3 was set for all host rocks.

• Effective RN diffusion coefficients

Here, the method used in H12 [3] [87] [88] was applied to take into consideration the dependence of the effective diffusion coefficient on rock porosity. Specifically, for each rock type, JAEA-DDB [77], includes the most recent diffusion data. For any host rock groundwater chemistry (see Table 3.3-16), the effective diffusion coefficient can be obtained using an empirical approximation for porosity correction (Supporting Report 6-21).

For the effective diffusion coefficient in granite, the JAEA empirical relationship [22] applies to all RNs irrespective of speciation and thus, for a defined porosity, the same value was set for all elements.

The Neogene and Pre-Neogene sediments contain a range of clay minerals that may influence the effective diffusion coefficient depending on the charge of chemical species, as was the case for the buffer. The JAEA-DDB [77] effective diffusion data were analysed to develop empirical functions relating these to species charge and rock porosity. The speciation of relevant elements was calculated as before, with effective diffusion coefficients set based on the charge of the predominant aqueous species (see Supporting Report 6-18), corrected for ambient rock temperature.

With regard to TRU waste Gr.3, assuming that nitrate flows into the host rock and the distribution of the chemical species may change, in order to be conservative, all elements are assigned an effective diffusion coefficient equal to the smallest among the calculated values.

The effective diffusion coefficients set and further supporting details are provided in Supporting Report 6-21.

• Sorption distribution coefficients

Sorption data for the different host rocks and specified groundwater chemistries were extracted from the JAEA-SDB [44] [82] [89]. In cases where data were lacking, chemical analogy was used to complete the database. For TRU waste Gr.3, the influences of increase in ionic strength due to the nitrate and possible complex formation with ammonia generated by reduction of nitrate are assessed. Since Cs, Sr, Ra and Pb do not form complexes, their sorption is affected by the ionic strength, whereas Co, Ni and Pd are assumed to form complexes. Sorption is conservatively not considered for RN migration analysis in the EDZ, since its thickness is limited and its assumed porosity is high.

The selected distribution coefficients are listed in Supporting Report 6-22. Further parameters used for the one-dimensional RN transport analysis are summarised in Table 6.4-1.

Table 6.4-1 THMC conditions set for the near field (1/2)

Set THMC conditions		
T	Temperature (°C)	Plutonic rocks, Pre-Neogene sediments: 45 Neogene sediments: 30
H	Hydraulic gradient	Plutonic rocks, Pre-Neogene sediments: 0.05 Neogene sediments: 0.06
	Hydraulic conductivity of buffer (m/s)	1.0×10^{-12} (H12V plutonic rock/Pre-Neogene sediments, TRU waste) 1.0×10^{-10} (PEM) 1.0×10^{-11} (Neogene sediments, TRU waste)
	Hydraulic conductivity of structural framework (m/s)	1.0×10^{-7} (up to 200 y after closure) 1.0×10^{-5} (after 200 y after closure)
	Hydraulic conductivity of vault infill (m/s)	1.0×10^{-5}
	Hydraulic conductivity of EDZ	100 times that of the host rock
	EDZ flow rate	Appendix Table 4
	Number of channels in model	41
	Multi-channel transmissivity (m^2/s)	The transmissivity (*Ti*) of each channel obtained by fitting to the particle tracking analysis result from Partridge (See 6.4.1 (2) (iv) (e))
	Open width of fracture (m)	Empirical relationship based on hydraulic conductivity of each channel given by *Ti* above
M		The influences of changes of the stress field on RN migration parameters are not considered
C	Porewater chemistry of buffer	Appendix Table 5
	Glass Overpack Porewater chemistry	Appendix Table 6
	Cementitious infill/backfill Porewater chemistry	Appendix Tables 7, 8

Table 6.4-1 THMC conditions set for the near field (2/2)

<table>
<tr><th colspan="4">Nuclide migration parameters</th></tr>
<tr><td rowspan="2">Waste</td><td colspan="2">Nuclide elution start time and Radioactive inventory at that time</td><td>- HLW
• Elution start time: 1 ky after closure
• Radioactive Inventory: See SR 2-3
- TRU waste
• Waste package A
✧ Elution start time: Immediately after closure
✧ Radioactive Inventory: Table 6.1-4
• Waste package B
✧ Elution start time: 300 y after closure
✧ Radioactive Inventory: See SR 2-3</td></tr>
<tr><td colspan="2">Nuclide dissolution rate (1/y)</td><td>- HLW: 1/65,270 (congruent with glass)
- TRU waste:
• Gr.1: instantaneous dissolution
• Gr.2: 1/11,400 (Zircaloy), 1/8,500 (stainless steel/inconel), instantaneous dissolution (other)
• Gr.3: instantaneous dissolution
• Gr.4: instantaneous dissolution</td></tr>
<tr><td rowspan="3">EBS</td><td colspan="2">Solubility</td><td>Appendix Tables 9 (Plutonic rocks), 10 (Neogene sediments), 11 (Pre-Neogene sediments)</td></tr>
<tr><td colspan="2">Effective diffusion coefficient</td><td>Appendix Tables 12 (Plutonic rocks), 13 (Neogene sediments), 14 (Pre-Neogene sediments)</td></tr>
<tr><td colspan="2">Sorption distribution coefficient</td><td>Appendix Tables 15 (Plutonic rocks), 16 (Neogene sediments), 17 (Pre-Neogene sediments)</td></tr>
<tr><td rowspan="8">Near field host rock</td><td rowspan="3">Fracture</td><td>Transfer distance (m)</td><td>100</td></tr>
<tr><td>Dispersion length (m)</td><td>10</td></tr>
<tr><td>Matrix diffusion flow wetted surface (%)</td><td>Plutonic rocks: 50, Neogene sediments: 100, Pre-Neogene sediments: 60</td></tr>
<tr><td rowspan="5">Substrate</td><td>Matrix diffusion depth (m)</td><td>Plutonic rocks: 0.1, Neogene sediments: 0.8, Pre-Neogene sediments: 0.5</td></tr>
<tr><td>Effective porosity (%)</td><td>Plutonic rocks: 0.8, Neogene sediments: 25, Pre-Neogene sediments: 3.5</td></tr>
<tr><td>Rock density (kg/m ^{3})</td><td>2,700</td></tr>
<tr><td>Effective diffusion coefficient</td><td>Appendix Tables 18 (Plutonic rocks), 19 (Neogene sediments), 20 (Pre-Neogene sediments)</td></tr>
<tr><td>Sorption distribution coefficient</td><td>Appendix Tables 21 (Plutonic rocks), 22 (Neogene sediments), 23 (Pre-Neogene sediments)</td></tr>
</table>

(3) Panel scale models and datasets

As described in Section 6.4.1 (2) (ii), at the near field scale, the models and datasets are developed for downflow waste packages in each panel and 100 m of host rock flow path. At the panel scale, the migration of RNs calculated in the near field scale was expanded by the following simple method and converted into a release rate from each disposal panel.

For HLW disposal in plutonic rocks, RN migration analysis at the panel scale is the same for both the H12V and PEM options. The near field model for calculated RN migration from a number (ni) of representative waste packages at the downflow end of disposal tunnels (φN(HLW), i (t)), for each disposal panel i[7]. This is converted to a release rate from the entire panel (φP(HLW), i (t)) by multiplying by the total number of waste packages in it. Here, conservatively, the impact of the up-flow waste packages suppressing the release of RNs from the EBS downstream is ignored (as in H12). This assumption is further justified by consideration that the flow in the rock takes place in a discrete fracture network, reducing the probability that the groundwater passing a waste package would also pass other waste packages. Also, as described in Section 4.5.4, a main access tunnel is located downstream at the edge of the disposal panel (separation distance 30 or 60 m from the nearest disposal tunnel), but such tunnels are not considered in the analysis (see Figure 6.4-4). The influence of such access tunnels on RN migration analysis was examined and confirmed that it is not significant (see Supporting Report 6-14).

For TRU waste in plutonic rocks, release rates of RNs on the panel scale are calculated for each waste group. Specifically, the calculated RN releases at near field scale for group j are used to derive a release rate (φN (TRU), j[8] (t)) from one disposal vault, which is then multiplied by the number of vaults, mj, for that group in order to assess the panel scale releases (φP (TRU), j (t)). As noted in Section 4.5.4, a main tunnel exists at a distance of about 30 m downstream of the disposal tunnel, within the area analysed at the near field scale, but, as for HLW, this is not considered (see Figure 6.4-5). Also, here the influence of such a tunnel on RN migration was examined separately and confirmed that it is not significant (see Supporting Report 6-14).

In the cases of both HLW and TRU waste in Neogene sediments, the near field RN migration model explicitly considers potential short circuits to access tunnels downstream (See Figure 6.4-4). Thus, the panel scale RN migration analysis considers the influence of the access tunnel at the downstream end of the vault on RN migration. As for HLW, this approach was also conservative in its treatment of the upstream vault.

The analysis models and approach for both HLW and TRU waste in Pre-Neogene sediments is the same as described for plutonic rock. The thermal and mechanical datasets used for RN migration analysis on the panel scale are the same as those for the near field. Regarding the geochemical conditions, the groundwater chemistry of the host rock may be changed by leachate from the disposal tunnels and other materials in the access tunnels, but the extent of change is assumed limited and its influence on mobility of RNs was ignored. This assumption is judged adequate for the HLW repository, since the source impact on groundwater chemistry is limited, but may need further analysis for the TRU repository. At the same time, such reactions also alter the backfill material in tunnels: the hydraulic conductivity of the backfilling material is set taking such alteration into account. Since the hydraulic plug is designed to maintain the same hydraulic conductivity as the host rock for a long period of time, it is not treated as a preferential migration route for RN migration analysis. Mechanical plugs are treated as having the same hydraulic characteristics as the backfill material. These hydraulic conditions are as shown in Table 6.4-1.

[7] Repository in plutonic rocks and Pre-Neogene sediments: i = 1 ... 6; Repository in Neogene sediments: i = 1 ... 8.

[8] *j* = 1, 2, 3, 4HD, 4HH, 4LC, 4LD

(4) Repository scale models and datasets

(i) Simplified RN migration model

Figure 6.4-16 shows the concept of the simplified model used for RN migration analysis on the repository scale.

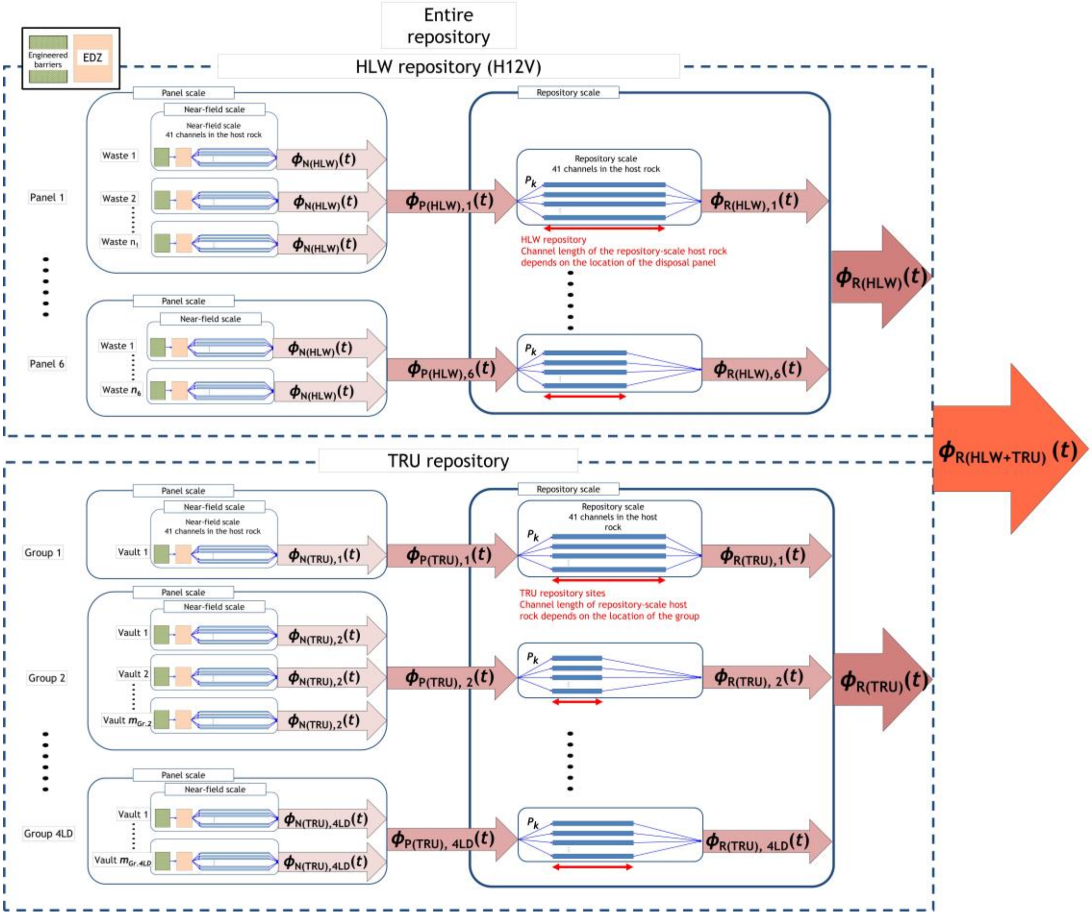


Figure 6.4-16 Overview of the simplified RN migration model - repository scale (HLW and TRU waste)

For HLW, the RN releases from the panel scale analysis described above, φP(HLW), i(t), are used for input to a multi-channel model, as described in Section 6.4.1 (2) (iv) (shown in Figure 6.4-7) to calculated transfer rate through repository scale host rock. More specifically, for each panel i with release rate φP(HLW), i(t), a multi-channel model of host rock with a distribution of hydraulic characteristics pk, for each channel k (k = 1,…, 41) is developed in a manner described in more detail below. This allows RN migration calculations using the GoldSim © code to determine releases at a repository scale, φR(HLW), i(t). Then, by summing releases from each panel, the release from the entire repository φR(HLW)(t) is calculated.

Similarly, for TRU waste, RN migration at the panel scale for each group j, φP(TRU), j(t), is used as input to the repository scale multi-channel model and summed to derive the total release from all groups, φR(TRU)(t). In the case of co-located disposal, the total release from the repository, φR(HLW + TRU)(t), is the sum of the releases from the two components (see Supporting Report 6-14).

Since the hydraulic conductivity of each channel within the multi-channel model of the repository host rock depends only on its large scale hydraulic and mass transfer characteristics, the same values are used for HLW and TRU waste. Hydraulic conductivities of each channel are derived from particle tracking analysis of the 3D DFN (analysis region 100 m x 100 m x 150 m), for non-sorbing tracers configured to approximate the actual groundwater flow, as discussed previously.

The channel lengths in the repository scale multi-channel depend on the location of the disposal panel, in the case of HLW, and the specific group disposal vaults, in the case of TRU waste. The repository layout at the disposal depth is set by selecting areas where the groundwater travel time is relatively long and the Darcy flow velocity is small, based on regional scale groundwater flow analysis. However, how this can be assured in practice at a given site will need more consideration. Although it is affected by the spatial distribution of anisotropic faults and by changes in local topography, it is assumed here that groundwater flows at repository depth roughly in a horizontal direction (see Supporting Reports 3-20, 3-21, 3-22). Therefore, for HLW, channel length from the down flow edge of each panel is determined by distance in the flow direction to a boundary (either a fault with length of 1 km or more[9], a TRU waste disposal area or a modelling area boundary), as shown in Figures 6.4-17, 6.4-18 and 6.4-19. However, such an assumption will need careful site specific assessment in the future.

Specifically for Pre-Neogene sediments, hydraulic characteristics may differ greatly in the region of a thrust fault and thus, when such areas lie on the line defining the channel length, only the distance within sound rock is considered. In the case where another disposal panel lies on a straight line connecting it to a downstream boundary, the migration through the downstream panel is conservatively excluded, i.e. by not adding the distance through the panel to the channel length. When the channel length is 100 m or less, it is treated as 0 m.

The procedure for selecting channel lengths for TRU waste was similar: as the footprint of this facility is relatively small, the separation of the entire repository from a boundary was used for all waste groups for both plutonic and Pre-Neogene host rocks, but distances from tunnels of the different waste groups are considered separately for the Neogene sediments due to layout adaptions, resulting in placing the TRU repository close to a water conducting fault. It is noted that the resulting very short channel lengths for the Neogene case could possibly have been increased by considering another layout.

For more details of the multi-channel model used for RN migration analysis on the repository scale, see Supporting Report 6-13.

(ii) Dataset for RN migration analysis at the repository scale

The RN migration parameters required for the multi-channel model at the repository scale are the same as those for the near field scale analysis, described in 6.4.1 (2) (v) (b) 3 and given in Table 6.4-1. The multi-channel hydraulic conductivities and channel lengths are given in Tables 6.4-2 to 6.4-4, which are set as described previously based on the reference repository layouts for the different host rocks shown in Figures 6.4-17, 6.4-18 and 6.4-19.

More details about setting channel lengths for the multi-channel model at the repository scale are provided in Supporting Report 6-13.

[9] Faults avoided when developing repository layout, as described in Chapter 4.

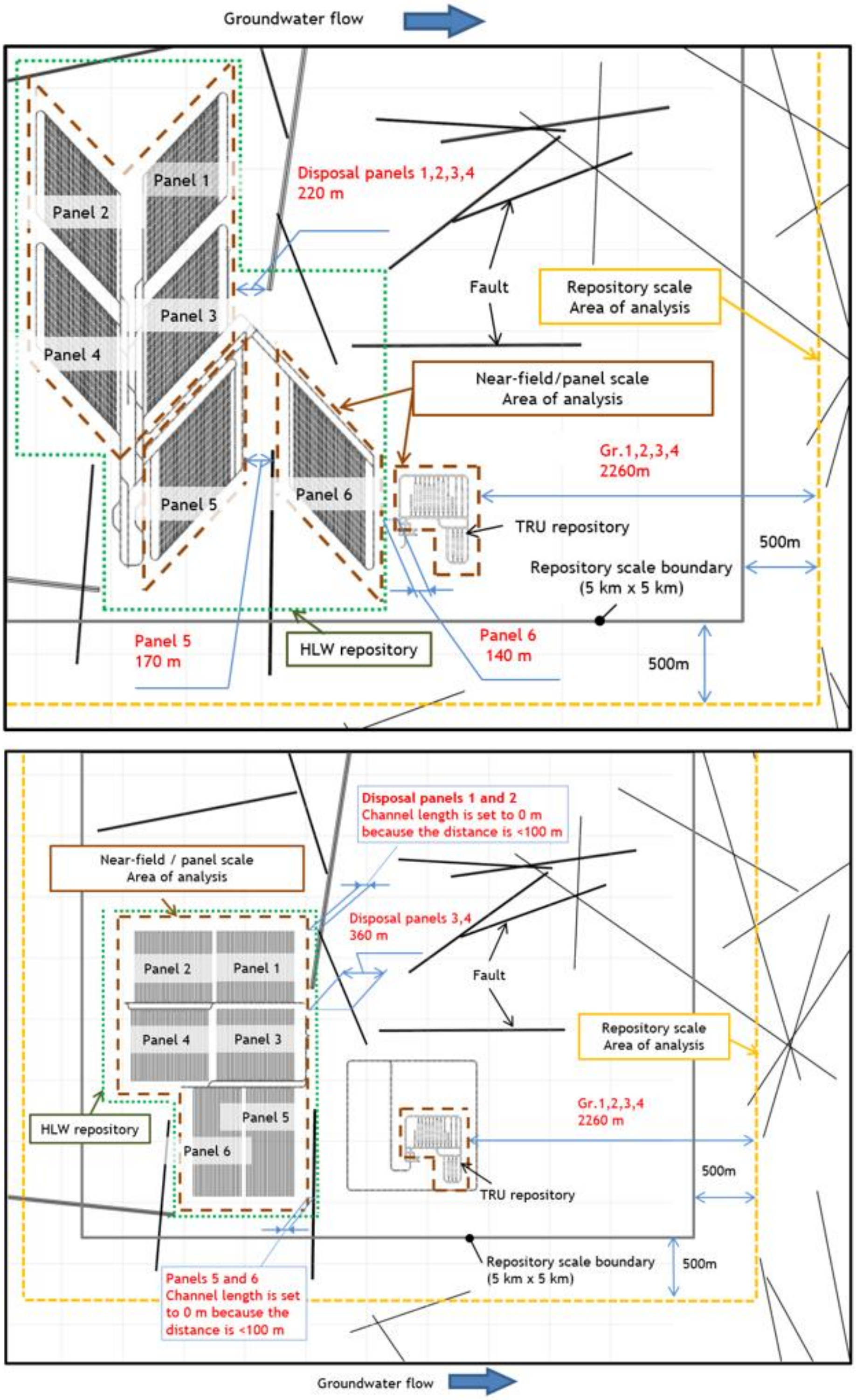


Figure 6.4-17 Set distances from the repository to model boundaries for reference layouts in plutonic rock (Upper: H12V, Lower: PEM, Gr.: Group)

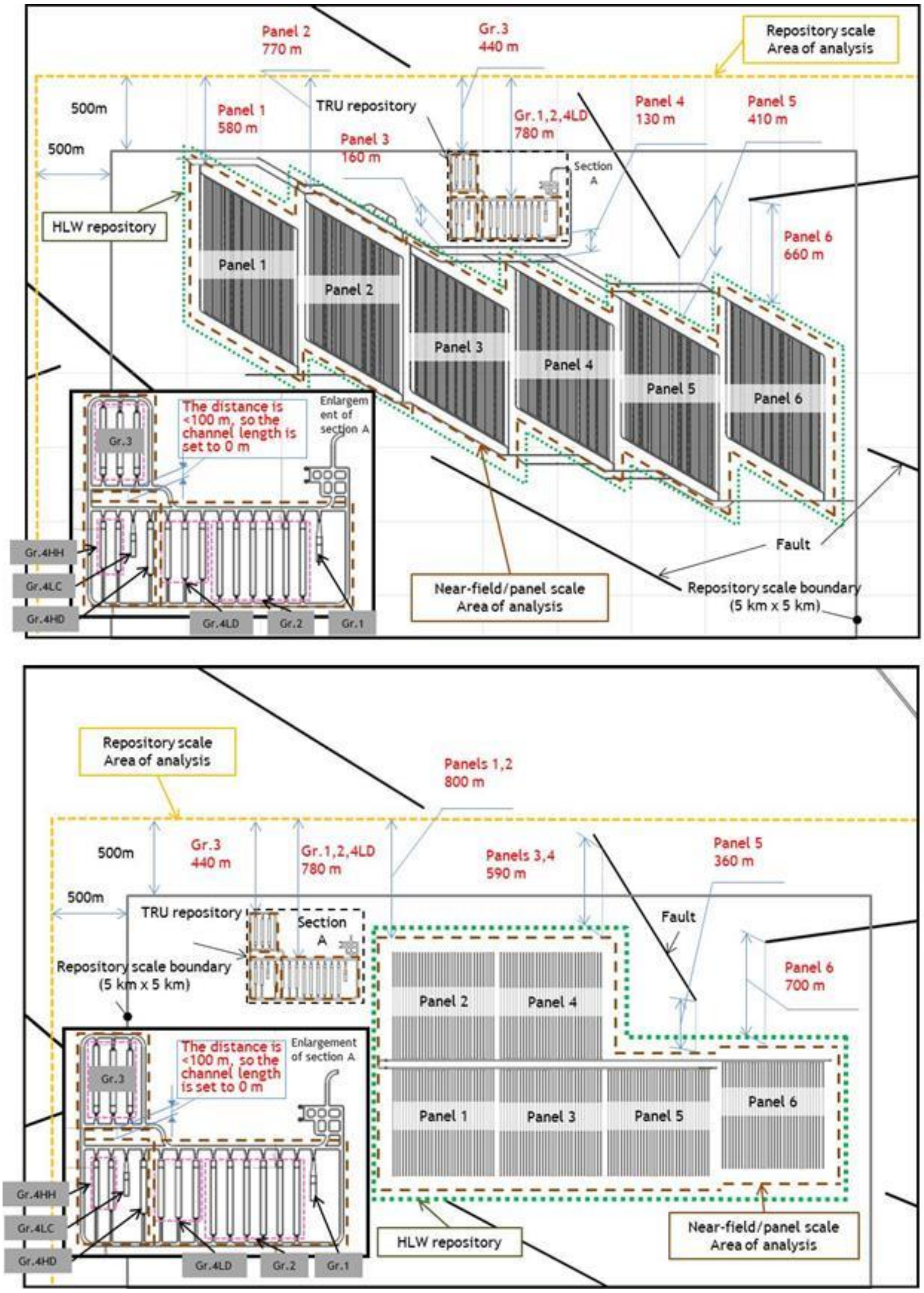
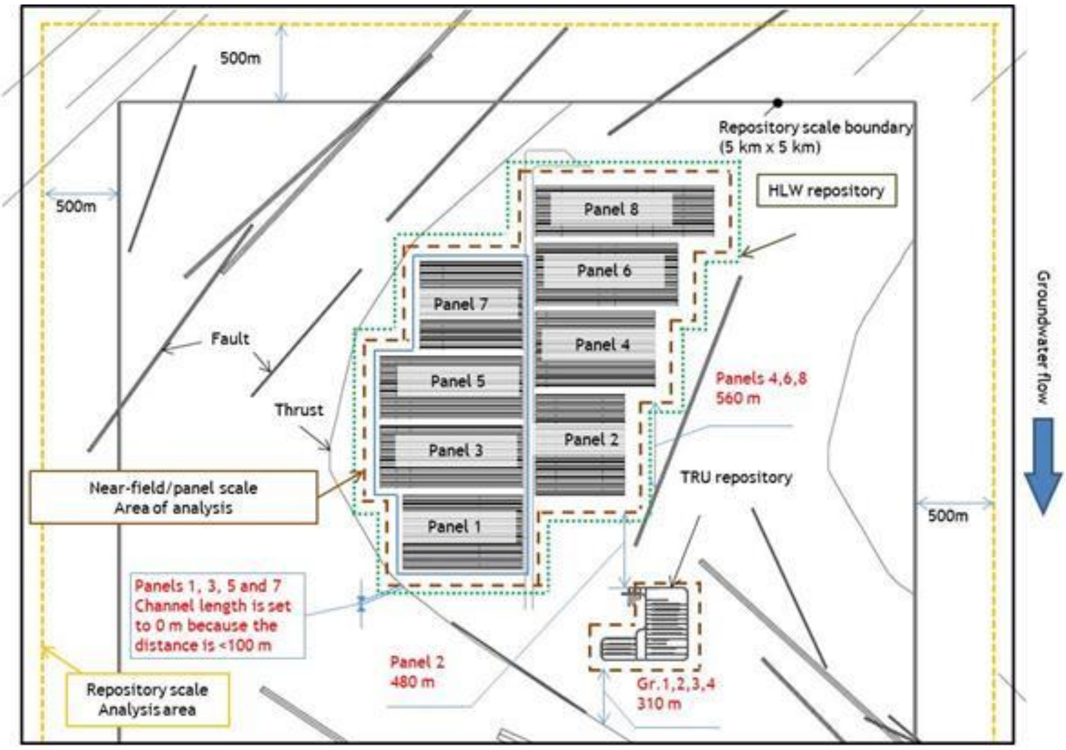


Figure 6.4-18 Set distances from the repository to model boundaries for reference layouts in Neogene sediments (Upper: H12V, Lower: PEM, Gr.: Group)



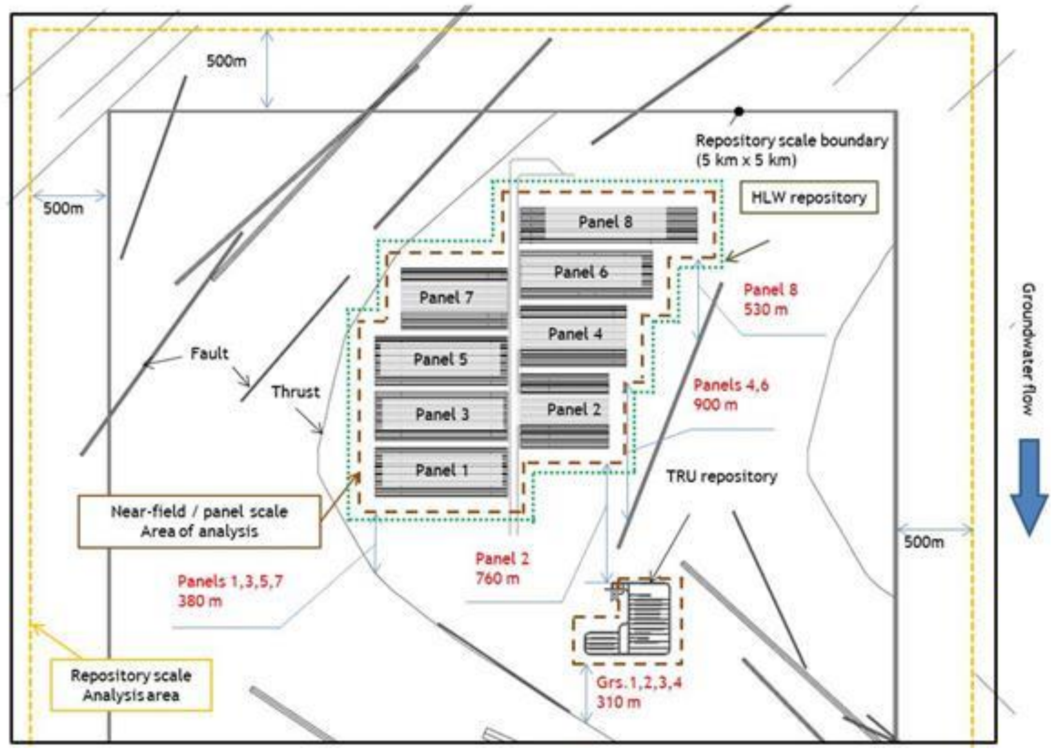


Figure 6.4-19 Set distances from the repository to model boundaries for reference layouts in Pre-Neogene sediments (Upper: H12V, Lower: PEM, Gr.: Group)

Table 6.4-2 Channel lengths for multi-channel model of plutonic rock (repository scale)

HLW disposal option	Waste disposal panel	Multi-channel model boundary	Model channel length (m)
H12V	1, 2, 3, 4	Fault > 1 km	220
	5	Fault > 1 km	170
	6	TRU waste disposal vault	140
	All Groups	Modelling area boundary	2,260
PEM	1, 2	Fault > 1 km	0
	3, 4	Fault > 1 km	360
	5, 6	Fault > 1 km	0
	All Groups	Modelling area boundary	2,260

Table 6.4-3 Channel lengths for multi-channel model of Neogene sediments (repository scale)

HLW disposal option	Waste disposal panel	Multi-channel model boundary	Model channel length (m)
H12V	1	Modelling area boundary	580
	2	Modelling area boundary	770
	3	TRU waste disposal vault	160
	4	TRU waste disposal vault	130
	5	Fault > 1 km	410
	6	Fault > 1 km	660
	Gr.1, Gr.2, Gr.4LD	Modelling area boundary	780
	Gr.3	Modelling area boundary	440
	Gr.4HH, Gr.4HD, Gr.4LC	Gr.3 disposal tunnel	0
PEM	1,2	Modelling area boundary	800
	3,4	Fault > 1 km	590
	5	Fault > 1 km	360
	6	Fault > 1 km	700
	Gr.1, Gr.2, Gr.4LD	Modelling area boundary	780
	Gr.3	Modelling area boundary	440
	Gr.4HH, Gr.4HD, Gr.4LC	Gr.3 disposal tunnel	0

Table 6.4-4 Channel lengths for multi-channel model of Pre-Neogene sediments (repository scale)

HLW disposal option	Waste disposal panel	Multi-channel model boundary	Model channel length (m)
H12V	1, 3, 5, 7	Thrust	0
	2	TRU waste disposal vault	480
	4, 6, 8	Fault > 1 km	560
	All Groups	Thrust	310
PEM	1, 3, 5, 7	Thrust	380
	2	TRU waste disposal vault	760
	4, 6	Fault > 1 km	900
	8	Fault > 1 km	530
	All Groups	Thrust	310

(5) Regional model and dataset

When conducting RN migration analysis on a regional scale, it is necessary to consider impacts of likely changes in the migration path due to topographic changes resulting from uplift/erosion, climate and sea level change, etc. Since such changes depend largely on the characteristics of the actual sites (as yet unspecified), as described in Section 6.4.1 (1), outside the repository scale, it was decided to apply a model in which all RNs are transferred to the biosphere via flow within large-scale faults. These large-scale faults are represented by an equivalent porous medium model, and parameters related to hydrogeology and RN transfer are set based on current understanding, as shown in Table 6.4-5 and with further background given in Supporting Report 6-23.

Table 6.4-5 Parameters for large faults

Parameter	Set value
Transport distance	700 m (plutonic rocks and Pre-Neogene sediments), 200 m (Neogene sediments)
Dispersion length	70 m (plutonic rocks and Pre-Neogene sediments), 20 m (Neogene sediments)
Hydraulic conductivity	1.0×10^{-5} m/s
Hydraulic gradient in fault	Plutonic rocks, Pre-Neogene sediments: 0.05 Neogene sediments: 0.06
Effective porosity	0.1
Density	2,700 kg/m^3
Effective diffusion coefficient	Appendix Tables 18 (Plutonic rocks), 19 (Neogene sediments), 20 (Pre-Neogene sediments)
Sorption distribution coefficient	Appendix Tables 21 (Plutonic rocks), 22 (Neogene sediments), 23 (Pre-Neogene sediments)

Since this fault model is very conservative, the dose results finally calculated using these models and parameters are almost the same as those obtained by directly inputting the flux of RNs output from the repository scale model directly into the biosphere model, showing that these do not have a significant impact (see Supporting Report 6-23). Therefore, the doses shown in the following (base cases Section 6.4.1 (7), variant cases Section 6.4.2) are calculated with the conservative assumption of repository scale releases directly into the GBI, the latter being modelled as a mixing tank with parameters representing the surface environment and not considering how it is actually connected to the flow paths. In addition, it is expected that the depth of the repository will change over the long-term due to uplift/erosion, which will change the fault length in the RN migration model for the regional scale and thus this approach is robust against such uncertainties. Other aspects of uplift/erosion are not considered in the current safety case, as previously discussed in Section 6.3.

(6) Biosphere model and dataset

In the safety assessment, for RNs released from the geosphere into the surface environment, the resultant consequences were modelled based on both migration processes in the biosphere and human lifestyle in the area impacted. In terms of biosphere evaluation, a general assessment method is illustrated in IAEA's international collaborative project BIOMASS [90], but it is noted, as highlighted in the H12 report, that the specific lifestyle of each country has to be taken into consideration. It is inherently difficult to assess human lifestyles and surface environmental conditions for long times into the future; thus, the future lifestyle (stylised) is generally assumed to be the same as at present, to form a basis for analysis of RN transfers in the biosphere and resultant doses (e.g., [25] [29]). In this report, the biosphere evaluation was conducted based on such an international approach.

The International Commission on Radiological Protection (ICRP) focuses on public protection and the determination of compliance with dose constraints, assessing doses to groups with relatively high exposure in order to define a “representative person” [91]. For the dose evaluation in this report, the radiation dose for such a representative individual was calculated and is compared to the dose constraints in Table 6.1-6. At present, since the repository sites are not decided, the biosphere will be evaluated by modelling potentially exposed groups as representative individuals, as described below. For details of the biosphere evaluation, see Supporting Report 6-1.

(i) Modelling of biosphere RN migration and resulting doses

Modelling migration processes and resultant radiation exposure in the surface environment is based on the latest developments in Japan and abroad [90] and proceeds as follows.

Firstly, the characteristics of the surface environment that influence behaviour of RNs released into the biosphere need to be considered; including the GBI, climate, geography/topography, surface hydrology, soil type, biota together with human activities and lifestyles. In this description, long-term surface evolution by climate change, uplift and erosion, etc. is also taken into consideration. Current anthropogenic climatic change impacts can also be considered in such scenarios, although this was not done in the present analysis. Next, individual environmental compartments (such as river water or soil) are identified and represented as boxes of fixed volume. While it is understood that the surface environment changes with time, these boxes are assumed to represent typical biosphere compartments also in the future. It is recognised that there are approaches for more explicitly considering changes to the surface environment that may be used in coming assessments. Processes are then identified that transport RNs between compartments and a box model is developed to quantify these, while assuring mass balance and accounting for impacts of RN decay and ingrowth.

Without a site being identified at present, conditions necessary for describing the biosphere system are derived from the previous H12 and TRU-2 studies. The Nationwide Map published recently [92] identified not only excluded areas (e.g., within a radius of 15 km from the centre of Quaternary volcanoes), but also scientifically favourable areas, which have an average altitude in the order of 100 m above sea level (Supporting Report 6-10). Such terrain is classified (according to [93]) as relatively low-lying plains. If the repository is assumed to be built in such a location, expected groundwater flow systems will result in releases to the surface being located downstream from the repository footprint, so it was considered reasonable for rivers in such plains to act as the GBI. The release into the river can then be passed to other compartments, such as irrigated farmland or the sea. A major river represents the most typical GBI in Japan, but, in a more site-specific assessment, it is understood that the GBI selection must be more representative of the site and could also consider other objects such as small aquifers and smaller rivers.

In addition, it is important to consider the temperate climate assumed in the biosphere assessment model, because the majority of areas in Japan today are in such a zone, and glaciated areas are limited to a few areas, even if long-term climate change is considered [94].

For the exposure process, the groups most likely to be exposed by RNs that reach the biosphere are identified, while taking into account the group lifestyle, food sources, drinking water, etc., in order to calculate internal doses by RN ingestion, respiration and external exposure.

Representative persons are selected from groups assumed to have relatively high radiation doses. In the H12 and TRU-2 reports, such groups included “farmers”, “freshwater fishermen” and “marine fishermen”, which are the focus also in this report. Dose conversion factors (see 6.4.1 (6) (iii) below) are calculated in the related compartments based on the assumed lifestyle for adults of these three groups.

An example of the exposure assessment for a representative person in the farmers group, with RN migration and uptake processes that assume a warm climate and a river water GBI, is shown in Figure 6.4-20.

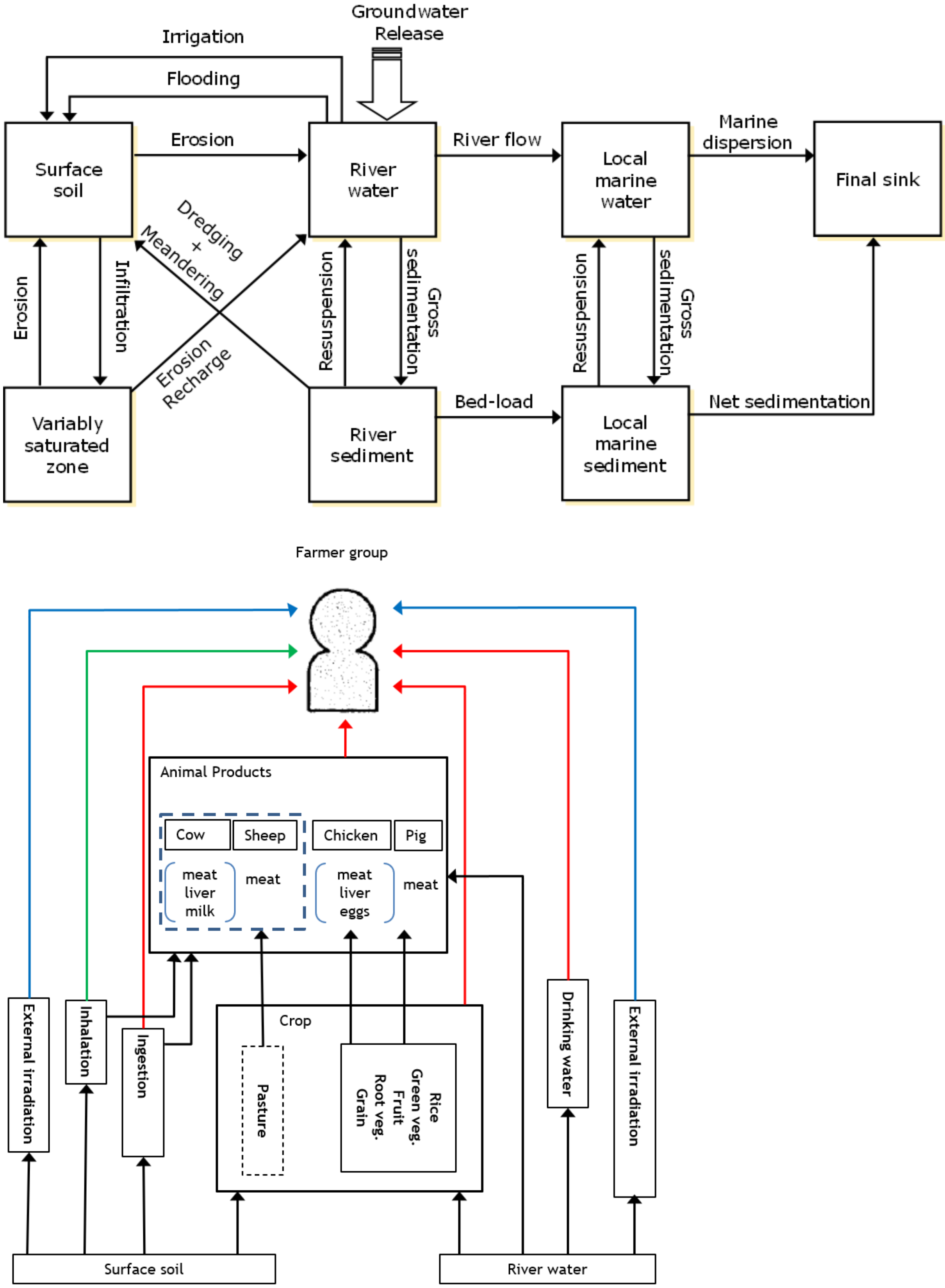


Figure 6.4-20 Example of RN migration and radiation exposure processes in the biosphere (River water GBI, temperate climate, farmer exposure group)

This model is the same as that used in the TRU-2 report. Each box in the figure represents a compartment in the biosphere: by solving simultaneous equations for mass balance during RN transfers between these compartments, the distribution of each RN can be calculated at each time step.

(ii) Dataset

As above, the required dataset, based on that used in both the H12 and TRU-2 reports, has been updated to reflect average and median values calculated from the latest statistical data on consumption, river flow, irrigation water, food production, etc. Thus, the latest knowledge about processes influencing RN transfer parameters in the surface were reflected in the effective dose conversion factors, which mirror the method of setting data in the latest Japanese biosphere evaluation [22]. Regarding the river flow rate, a logarithmic mean value was derived from the statistical data, assuming that it reflects a lognormal distribution. In the H12 and TRU-2 reports, the river flow was set as a conservative value based on the nationwide data on class A rivers[10]. The value of river flow set in this report uses the average value of such data, since this is judged more representative before sites are selected. This is about 10 times the value used in the H12 and TRU-2 reports (same as the applied value in [22]). Details on the selection of the dataset are given in Supporting Report 6-1.

(iii) Setting the dose conversion factor for a representative individual

The dose conversion factor relating exposure dose to the input flux of RNs at steady state is directly derived by the biosphere model used in the H12 and TRU-2 studies. RN redistribution times in the biosphere are shorter than the transit time from the repository to the GBI, so use of such steady-state values in the safety assessment is justified and doses are simply obtaining by multiplying the input rate of the RNs flowing into the biosphere by these factors. In this report, this method was applied and dose conversion factors calculated using various biosphere models and corresponding datasets. For the representative persons, an example of dose conversion factors is shown in the Table 6.4-6, including modelled doses to agricultural workers as shown in Figure 6.4-20. It may be noted that, despite a much higher dilution in the sea water compartment, the dose conversion factors to the marine fishery group are higher for C-14 compared to the other groups and not much less for other RNs. This is due to the modelled bio-accumulation of C-14 in the marine ecosystem and the eating habits assumed for the different representative groups.

[10] Rivers that are part of river systems considered to be particularly important for the maintenance of the land or national economy. These rivers are designated by the Minster of Land, Infrastructure and Transport. N.B. This footnote is not included in the Japanese version of the report.

Table 6.4-6 Dose conversion factors for representative persons (river water GBI, temperate climate) (1/2)

(Sv/y)/(Bq/y)

Nuclide	Farmer group	Freshwater fishery group	Marine fishery group
C-14	1.6×10^{-18}	5.8×10^{-18}	2.0×10^{-17}
Cl-36	6.3×10^{-18}	7.4×10^{-19}	1.2×10^{-22}
Co-60	3.9×10^{-17}	6.9×10^{-17}	1.3×10^{-17}
Ni-59	3.6×10^{-17}	4.4×10^{-20}	1.4×10^{-19}
Ni-63	1.5×10^{-17}	9.6×10^{-20}	3.2×10^{-19}
Se-79	8.4×10^{-16}	1.9×10^{-18}	2.8×10^{-17}
Sr-90	3.8×10^{-16}	2.0×10^{-17}	2.1×10^{-19}
Zr-93	2.9×10^{-18}	8.2×10^{-19}	2.7×10^{-18}
Nb-93m	1.4×10^{-19}	8.1×10^{-20}	7.5×10^{-20}
Nb-94	1.8×10^{-15}	1.2×10^{-16}	2.7×10^{-17}
Mo-93	1.9×10^{-17}	2.0×10^{-18}	1.8×10^{-19}
Tc-99	4.6×10^{-18}	3.9×10^{-19}	2.6×10^{-18}

Table 6.4-6 Dose conversion factors for representative persons (river water GBI, temperate climate) (2/2)

(Sv/y)/(Bq/y)

Nuclide	Farmer group	Freshwater fishery group	Marine fishery group
Pd-107	1.0×10^{-18}	2.3×10^{-20}	3.1×10^{-20}
Sn-126	2.9×10^{-15}	1.4×10^{-16}	4.4×10^{-15}
I-129	2.6×10^{-16}	7.0×10^{-17}	4.1×10^{-17}
Cs-135	7.2×10^{-17}	4.9×10^{-18}	2.6×10^{-19}
Cs-137	1.1×10^{-16}	1.1×10^{-16}	7.2×10^{-18}
Cm-248	6.5×10^{-15}	2.3×10^{-15}	1.0×10^{-14}
Pu-244	1.4×10^{-15}	2.4×10^{-16}	4.1×10^{-16}
Cm-244	1.4×10^{-16}	1.0×10^{-16}	1.6×10^{-15}
Pu-240	9.1×10^{-16}	1.6×10^{-16}	4.1×10^{-16}
U-236	1.8×10^{-16}	2.9×10^{-17}	8.2×10^{-19}
Th-232	2.4×10^{-14}	3.4×10^{-16}	1.0×10^{-15}
Ra-228	8.7×10^{-16}	7.1×10^{-16}	7.1×10^{-16}
Th-228	1.5×10^{-16}	1.5×10^{-15}	2.1×10^{-16}
Np-236	6.8×10^{-16}	1.1×10^{-17}	9.2×10^{-18}
Pu-236	8.3×10^{-17}	5.7×10^{-17}	1.4×10^{-16}
U-232	7.8×10^{-16}	2.1×10^{-16}	8.5×10^{-18}
Cm-245	2.0×10^{-15}	3.1×10^{-16}	2.8×10^{-15}
Pu-241	1.6×10^{-17}	3.1×10^{-18}	8.0×10^{-18}
Am-241	5.6×10^{-16}	1.6×10^{-16}	1.8×10^{-15}
Np-237	1.9×10^{-15}	7.0×10^{-17}	5.9×10^{-17}
Pa-233	9.3×10^{-19}	6.2×10^{-18}	2.8×10^{-19}
U-233	2.9×10^{-16}	3.1×10^{-17}	9.0×10^{-19}
Th-229	3.3×10^{-15}	8.5×10^{-16}	1.0×10^{-15}
Cm-246	1.1×10^{-15}	1.8×10^{-16}	2.7×10^{-15}
Pu-242	9.5×10^{-16}	1.6×10^{-16}	3.9×10^{-16}
U-238	1.9×10^{-16}	3.0×10^{-17}	9.2×10^{-19}
Am-242m	4.4×10^{-16}	1.6×10^{-16}	1.7×10^{-15}
Pu-238	2.7×10^{-16}	1.5×10^{-16}	3.8×10^{-16}
U-234	2.3×10^{-16}	3.0×10^{-17}	8.6×10^{-19}
Th-230	8.4×10^{-15}	1.5×10^{-16}	3.4×10^{-16}
Ra-226	1.6×10^{-14}	5.7×10^{-16}	4.0×10^{-16}
Pb-210	1.3×10^{-15}	4.7×10^{-16}	8.0×10^{-16}
Po-210	1.3×10^{-15}	1.8×10^{-15}	2.8×10^{-14}
Cm-247	1.9×10^{-15}	6.8×10^{-16}	2.6×10^{-15}
Cm-243	1.9×10^{-16}	3.3×10^{-16}	2.0×10^{-15}
Am-243	1.5×10^{-15}	3.3×10^{-16}	1.8×10^{-15}
Pu-239	9.7×10^{-16}	1.6×10^{-16}	4.1×10^{-16}
U-235	4.0×10^{-16}	3.2×10^{-17}	1.4×10^{-18}
Pa-231	1.7×10^{-14}	4.7×10^{-16}	2.6×10^{-16}
Ac-227	1.6×10^{-15}	9.2×10^{-16}	1.0×10^{-15}

As described in Section 6.4.1 (6) (i), assuming a river or marine GBI in a lowland plain area, the doses are calculated for the above three groups in the corresponding biosphere systems. Comparing the conversion coefficients for the different representative groups shows that, the conversion factor for farmers, with the river GBI, almost always is higher than the conversion factors for the marine fishermen due to the much higher dilution in the sea compartment. Considering the possible impacts on lifestyle due to climatic change, it is considered that assuming current temperate conditions is conservative.

For the calculations of dose in this report, the dose conversion factors to farmers living in a temperate climate with a river GBI was applied to all analysis cases.

Dose conversion factors for farmers for a representative person after the updating the dataset result in changes relative to the H12 and TRU-2 studies, as illustrated in Figure 6.4-21.

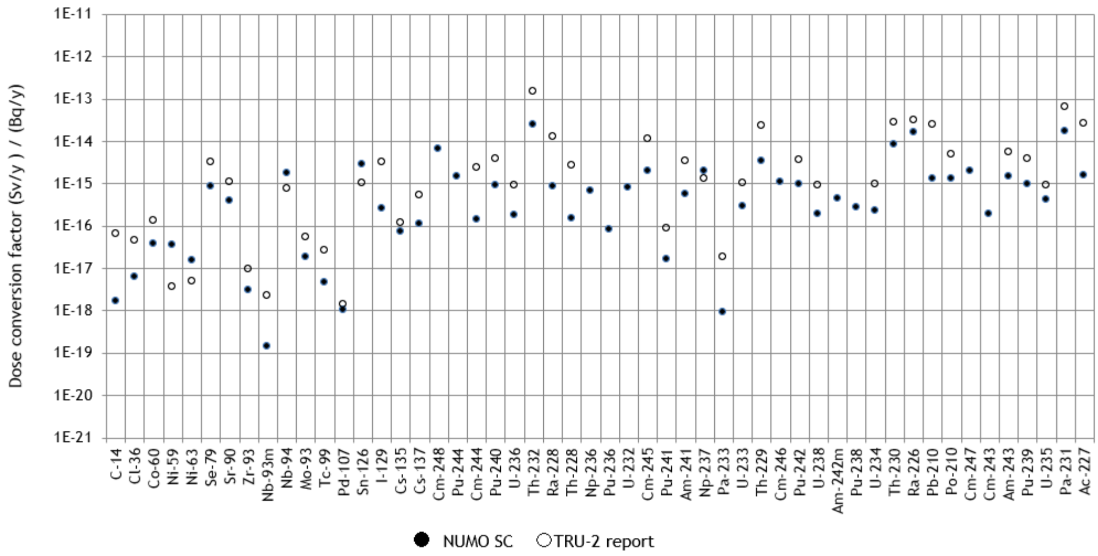


Figure 6.4-21 Dose conversion factor for farmers (GBI river water, temperate climate)

In comparison with the dose conversion factors in the TRU-2 report, values for Ni-59, Ni-63, Nb-94, Sn-126 and Np-237 have increased, despite the increased dilution resulting from the increased river flow. This is due to a major revision of the data base concerning the amount of food ingestion, distribution coefficients (Kd values) and corrections of half-lives for these RNs, where the Kd has increased two orders of magnitude for Np and about one order of magnitude for Nb and Sn compared to the TRU-2 study. The assumed half-life of Ni-59 has increased by about 25% since the time of the TRU-2 report publication. Data for other RNs have also changed. Furthermore, the impact of these changes depends on the combination of data, which for some RNs makes the irrigated agricultural land the dominating pathway instead of the drinking water pathway. Values for all other RNs have decreased, generally by about an order of magnitude due to the larger river flow now assumed resulting in an order of magnitude more dilution and reduction of dose to the farmer by the same factor [22].

(7) Results for the base cases

This report focuses on sites with co-location of disposal facilities for HLW and TRU waste, with the options shown in Table 6.1-1 taken into consideration. Based on the models and parameters presented in Sections 6.4.1 (2)-(6) above, the dose assessments of the base cases for these options are now presented. For more details on these calculations, see Supporting Reports 6-24, 6-25 and 6-26 for plutonic rocks, Neogene sediments and Pre-Neogene sediments, respectively.

In the following, figures showing the results of assessments for the base scenario (See Table 6.1-6) present annual effective doses to the reference person and also show that due to natural radiation in Japan (2,100 μSv/y), which helps put the results in context.

(i) Dose from the entire repository

Safety assessment of the repository as a whole was carried out by summing contributions from both HLW and TRU waste. As mentioned in Section 6.4.1 (2) (v) (a) 4., uncertainty in groundwater chemistry is captured by two model waters (with low and high salinity). HLW assessments include the H12V and PEM options while, for TRU waste, two kinds of containers are considered: A (loss of containment immediately after closure) and B (loss of containment 300 y after closure). By combining these, a total of 8 base case variants for each host rock will be considered.

Figure 6.4-22 shows the calculated results. In all cases, the maximum dose is less than 10 μSv/y, set as the target dose for the base scenario. As discussed in Section 6.1.5 (2) (i), this provides a good argument for safety.

For Figure 6.4-22 and similar figures thereafter, the following assumptions are made:

- For all waste packages, the timing of contact between the waste package and groundwater and the start of RN leaching:
    - for vitrified waste: 1,000 years after closure of the repository
    - for waste package A: immediately after closure of the repository
    - for waste package B: 300 years after repository closure
- Dose calculation using RN migration rates from repository scale host rock as direct input to the biosphere

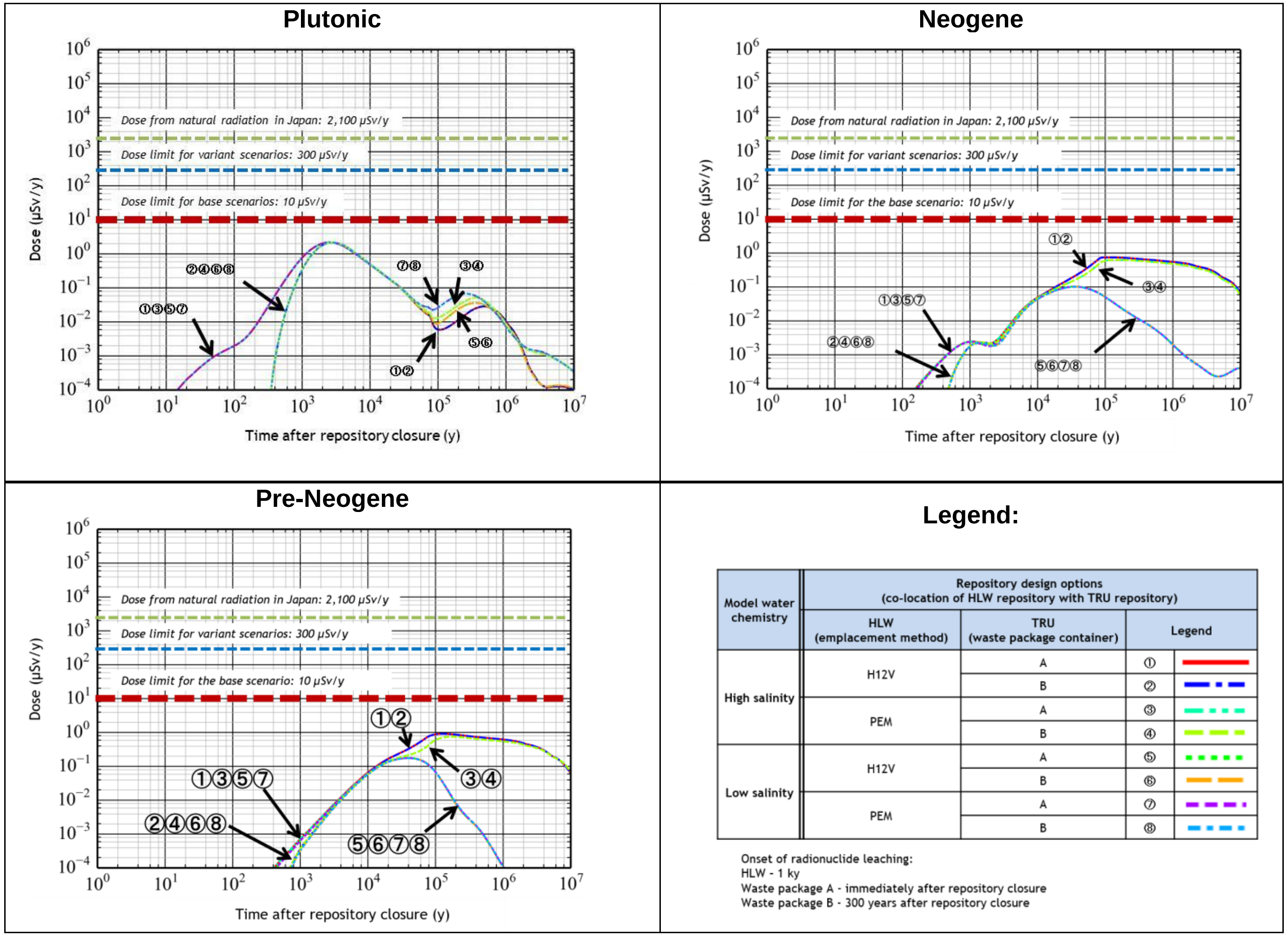


Figure 6.4-22 Doses from the entire facility for each of the disposal options (Base case)

In terms of groundwater chemistry variants, in plutonic rock there is little difference in dose curves for the two model waters but, for both sedimentary rocks, dose peaks are significantly higher for the high salinity cases. This will be further discussed below. For the two HLW disposal options, the calculated doses were effectively identical in all host rocks; this reflects the simplifications adopted in the near field transport model, lack of optimisation of repository layout and, in particular, the dominant contribution of TRU waste to total dose, so should not be over-interpreted.

In terms of TRU waste variants, in the case of waste package A, the conservative assumption is made that elution of RNs begins immediately after closure, hence initial breakthrough occurs earlier, but the dose maximum is effectively the same as that for waste package B. Below, the results of dose evaluation will be discussed in more detail.

(ii) RNs that dominate dose

As described above, there are almost no differences in the dose evaluation results between the H12V and PEM variants with regard to calculated doses, due to the simplifications adopted in the near field transport model, Therefore, the following discussion will focus on H12V. It is noted, however, that a more detailed near field model may have resulted in differences and also that there are several differences between the concepts with regard to handling and ease of installation, as discussed in Chapter 4.

(a) Plutonic rocks (see Supporting Report 6-24)

Figure 6.4-23 shows the separate doses resulting from HLW and TRU waste in plutonic rocks and the main RNs contributing to them. By comparing Figure 6.4-22 and Figure 6.4-23, it is clear that in all cases, RNs which dominate dose up to 100 ky are derived from TRU waste, in particular I-129, giving a maximum dose of about 2 μSv/y after about 3 ky This report conservatively sets the amounts of I-129 and Cl-36 in the HLW inventory and so, unlike in the H12 study, these are listed as the target RNs (Section 6.1.3). However, contribution to the maximum dose of the entire repository is mostly I-129 derived from TRU waste.

I-129 is dominant due to use of a conservative TRU Gr.1 model with a mixed tank source term after instantaneous release from the waste matrix. This is combined with modelled speciation as the stable iodide anion, with no solubility limit, zero sorption and lack of significant radioactive decay due to its very long half-life (1.6×10^7 y). Cl-36 has similar chemical characteristics and a long half-life (3.0×10^5 y), so its contribution to the dose is significant, even if I-129 dominates by a factor of 10 for HLW and very much more for TRU waste.

Even though models for such timescales must be treated with great caution, after 100 ky dose is dominated by Se-79 from HLW. This is because Se, though very mobile, reacts with iron derived from overpacks, buffer, pyrite in host rock, etc. and precipitates as iron diselenide. Nevertheless, the model predicts anionic speciation, and hence very low sorption in buffer and host rocks combines with a long half-life (3.0×10^5 y) to give significant releases.

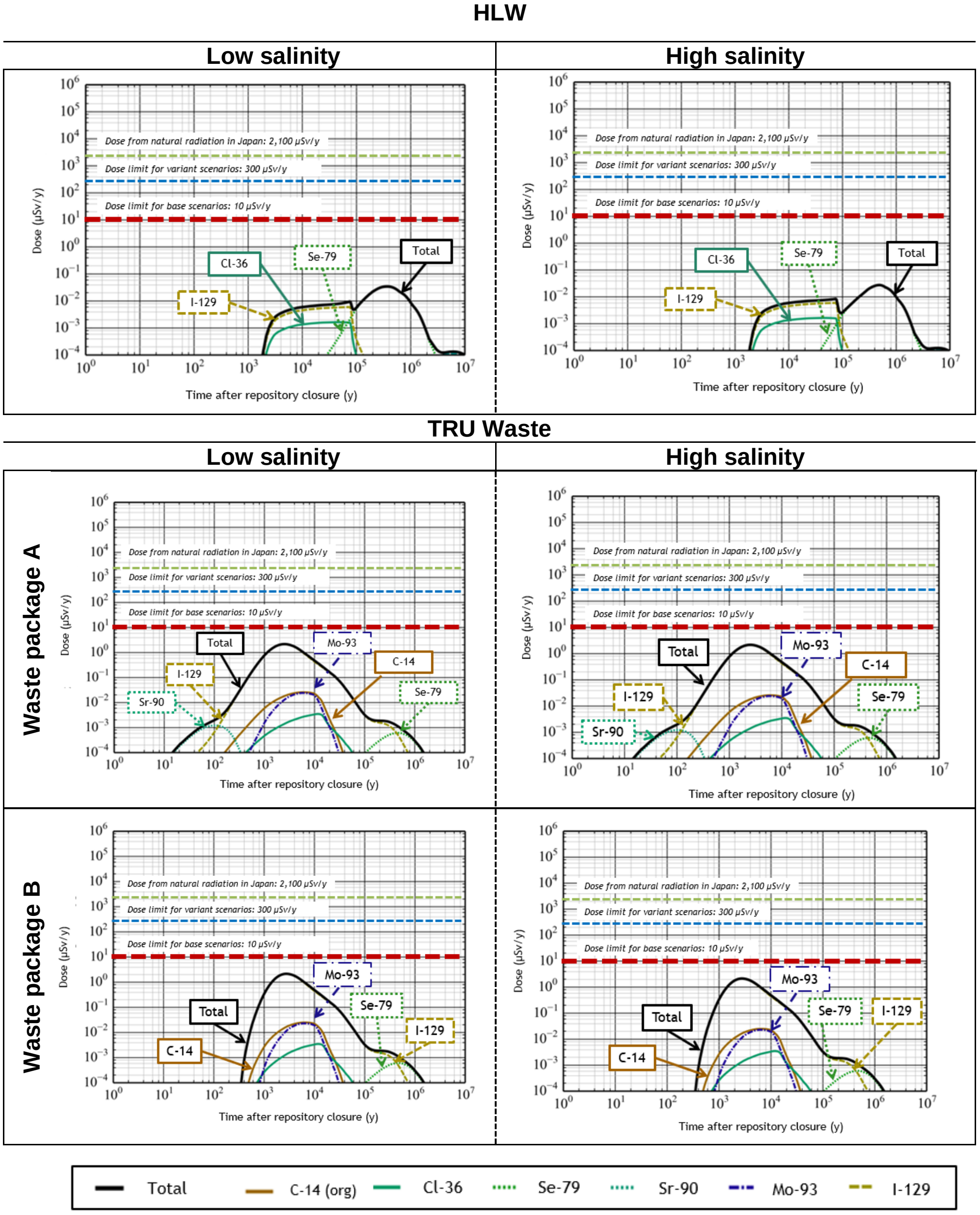


Figure 6.4-23 Doses and dominant RNs for plutonic repository (base case)

Regarding the cases with early calculated doses, combinations of conservatisms lead to results that should be considered more as “What if?” cases, rather than any kind of quantitative assessment of credible system evolution. This is particularly evident for TRU waste, where the mixing tank model of release from the EBS ignores the time required for repository re-saturation and failure of waste containers, constraints set by leaching of the waste matrix and slow RN diffusion through the infilled vault and the surrounding structural concrete.

As it is assumed that elution of RNs begins immediately after closure for TRU waste package A, the combination of very conservative transport properties (see Supporting Report 6-21 and Supporting Report 6-22) result in very short-lived Sr-90 (30-y half-life) from Gr.3 giving an early dose breakthrough, even though its value is extremely small. It is certain that this Sr-90 peak will disappear if more realistic modelling was done, which will be necessary to allow future assessment of varying EBS concepts for TRU waste. As such, features like breakthrough of short lived RNs and associated relatively high dose maxima are again artefacts resulting from the model and should not be over-interpreted.

Because the two model waters in plutonic rocks are similar, the values of RN transfer parameters such as solubility, distribution coefficient and diffusion coefficient are similar, so the calculated doses are almost the same.

(b) Neogene sediments (see Supporting Report 6-25)

Figure 6.4-24 shows the doses resulting from HLW and TRU waste in Neogene sediments and the main RNs contributing to them.

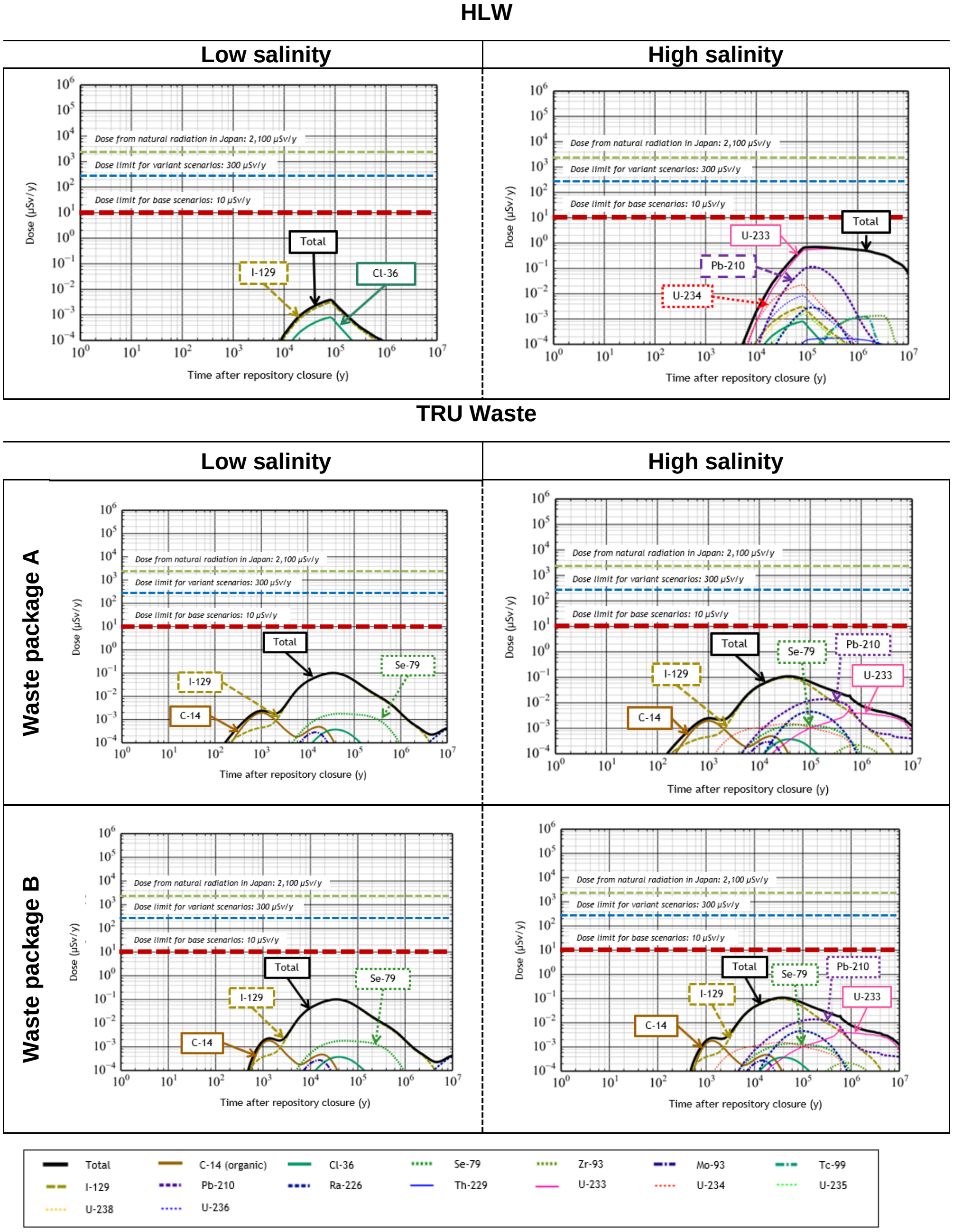


Figure 6.4-24 Doses and dominant RNs for Neogene repository (base case)

For low salinity water, by comparing Figures 6.4-22 and 6.4-24, it is clear that the dose is dominated by TRU for the entire evaluation period. The dominant RN in the TRU waste is initially C-14 from Gr.4, but then I-129 from Gr.1, giving a maximum dose of about 0.1 μSv/y (after 35 ky). The reason why C-14 peak arrives earlier than I-129 is an artefact of the reference layout (Figure 6.4-17) and the simplified model assumptions. Although all Gr.4 is the same distance from the model boundary, that upstream of Gr.3 (Gr.4H, the main source of C-14) is treated as if the migration distance was zero (as the distance to the nearest TRU vault is < 100 m). Again, this emphasises the need for a more realistic model to assess TRU waste disposal variants. The large impact of I-129 is explained as for the plutonic rock case.

In the case of high salinity groundwater, up to about 40 ky after closure, the situation is similar, with TRU waste dominating: initially C-14 from Gr.4 and then I-129 from Gr.1. Thereafter, however, the situation changes completely with the maximum dose from the entire repository after about 120 ky (0.7 μSv/y) predominantly due to U-233 from HLW.

Such unusual mobility of U in this reducing environment is due to the carbonate concentration of the high salinity groundwater set for Neogene sediments (about 40 mM, compared to about 2 mM for low salinity Neogene groundwater and about 0.2 mM for the high salinity plutonic rock). From calculations using the latest thermodynamic data, U forms stable anionic carbonate complexes in both buffer porewater and groundwater in this case, thus stabilising the VI valent oxidation state (particularly $UO_2(CO_3)_3^{4-}$ and $UO_2(CO_3)_2^{2-}$). No sorption data on such species in a reducing environment were found, but experimental studies of sorption of this kind of anionic complex in an oxidising environment indicate that sorption partition coefficients on clay minerals are extremely small [95]. Based on these factors, U is assigned a high solubility and an extremely small sorption distribution coefficient on host rock, causing U-233 to become the dominant RN. However, the approach may be overly conservative as neither sorption of such complexes onto carbonate minerals nor microbial utilisation of U(VI) under reducing conditions has been assessed.

The reason why U-233, with a half-life of 1.6 x 10^5 y, dominates the dose over such a long period is due to continuous ingrowth from its parent Np-237 (with a half-life of 2.1 x 10^6 y), which will remain in the buffer and rock for long times due to its low solubility and high sorption. The difference between peaks from U-233 originating from HLW and TRU is basically due to the fact that the inventory of Np-237 is higher in HLW than in TRU waste.

It is also noticeable that, after about 100 ky after closure, there is a major contribution of Pb-210 (half-life 22 years), derived mainly from HLW but also from TRU waste Gr.4. At this time, Pb-210 and its parent Ra-226 (half-life 1600 y) would normally be expected to be in secular equilibrium with Th-230 (half-life 7.5 x 10^4 y). The dose calculation considers the behaviour of relevant daughters in the decay chains and hence the inventory of Th-230 increases due to ingrowth from U-234, itself supported by ingrowth from Pu-242 (with a half-life of 3.8 x 10^5 y) which, as for Np-237, is effectively immobile due to its low solubility and high sorption. For Pb-210, it is considered that it can form a stable carbonate complex in groundwater; however, there are no sorption data for the carbonate concentrations and chemistry of the high salinity groundwater and hence the distribution coefficient on the host rock is very conservatively set to zero. The Pb-210 doses are thus determined by the migration of Ra-226 from HLW and the different TRU waste sources and its rapid transport to the biosphere when it is generated by Ra-226 decay.

It is clear that, unlike the plutonic case, there is little difference in the resultant doses from TRU waste packages A and B, apart from an earlier breakthrough of low levels of C-14 and I-129. In particular, this is due to distribution coefficients for Sr-90 set one or more orders of magnitude larger, allowing effectively complete decay of this short-lived RN (half-life 29 years).

The fact that C-14 does not contribute to the initial doses of plutonic rocks is due to much longer modelled migration distance for the repository scale, allowing for greater retardation of this RN by matrix diffusion. In terms of dose from I-129, the Neogene sediments maximum is about an order of magnitude less than that for plutonic rocks. This is because, as described in Section 6.4.1 (2) (v) (b) 3., for the Neogene sediments, the multi-channel model of the host rock assumes double the flow wetted surface and eight times the matrix diffusion depth of the plutonic rock case (see Appendix Figures 1 and 2), causing much greater dispersion of the release plume.

For plutonic rock, the dose of Se-79 dominates for times > 100 ky. For Neogene sediments, the dose contribution from Se-79 is negligibly small for HLW and of second order importance for the TRU waste. This can be explained by the sorption coefficient of Se-79 for the Neogene sediments, which is about 40 times higher for the low salinity case for plutonic rocks and about 50 times higher for the high salinity case. For TRU waste, similar sorption distribution coefficients are set, but modelled migration distances from the disposal vaults are conservatively set to be much shorter than from HLW panels, as explained previously, which means that Se-79 from the TRU waste is not as well retarded as that originating from HLW.

In the case of the plutonic rocks, Sr-90 in Gr.3 and other waste packages is the dominant RN in the initial very small dose to the whole repository for any model water chemistry in Waste Package A. For the Neogene sediments, the host rock Kd of Sr-90 is significantly higher than the plutonic case (25 times higher in low salinity groundwater and 8.75 times higher in high salinity groundwater) and its half-life is relatively short (29 years), so it decays to insignificance during migration. The reason why C-14 does not contribute to the initial dose of the entire repository for plutonic rocks is that the RN migration distance at the repository-scale is long enough to allow significant retardation caused by matrix diffusion.

(c) Pre-Neogene sediments (see Supporting Report 6-26)

Figure 6.4-25 shows the doses resulting from HLW and TRU waste in Pre-Neogene sediments and the main RNs contributing to them.

For low salinity water, by comparing Figures 6.4-22 and 6.4-25, it is clear that again the dose is dominated by TRU for the entire evaluation period. The dominant RN in the TRU waste is I-129 derived from Gr.1, giving a maximum dose of about 0.2 μSv/y (after 40 ky). The large impact of I-129 is again due to use of a conservative model of instantaneous release unconstrained by solubility limits after package failure and, as a stable anion, assigned zero sorption and lack of significant radioactive decay due to its very long half-life.

For HLW, the breakthrough is different from the plutonic rock case but very similar to the Neogene case apart from a significantly longer release tail. This is because, as described in Section 6.4.1 (2) (v) (b) 3., for Neogene sediments, the multi-channel model of the host rock assumes greater flow wetted surface and matrix diffusion depth, causing much greater dispersion of the release plume.

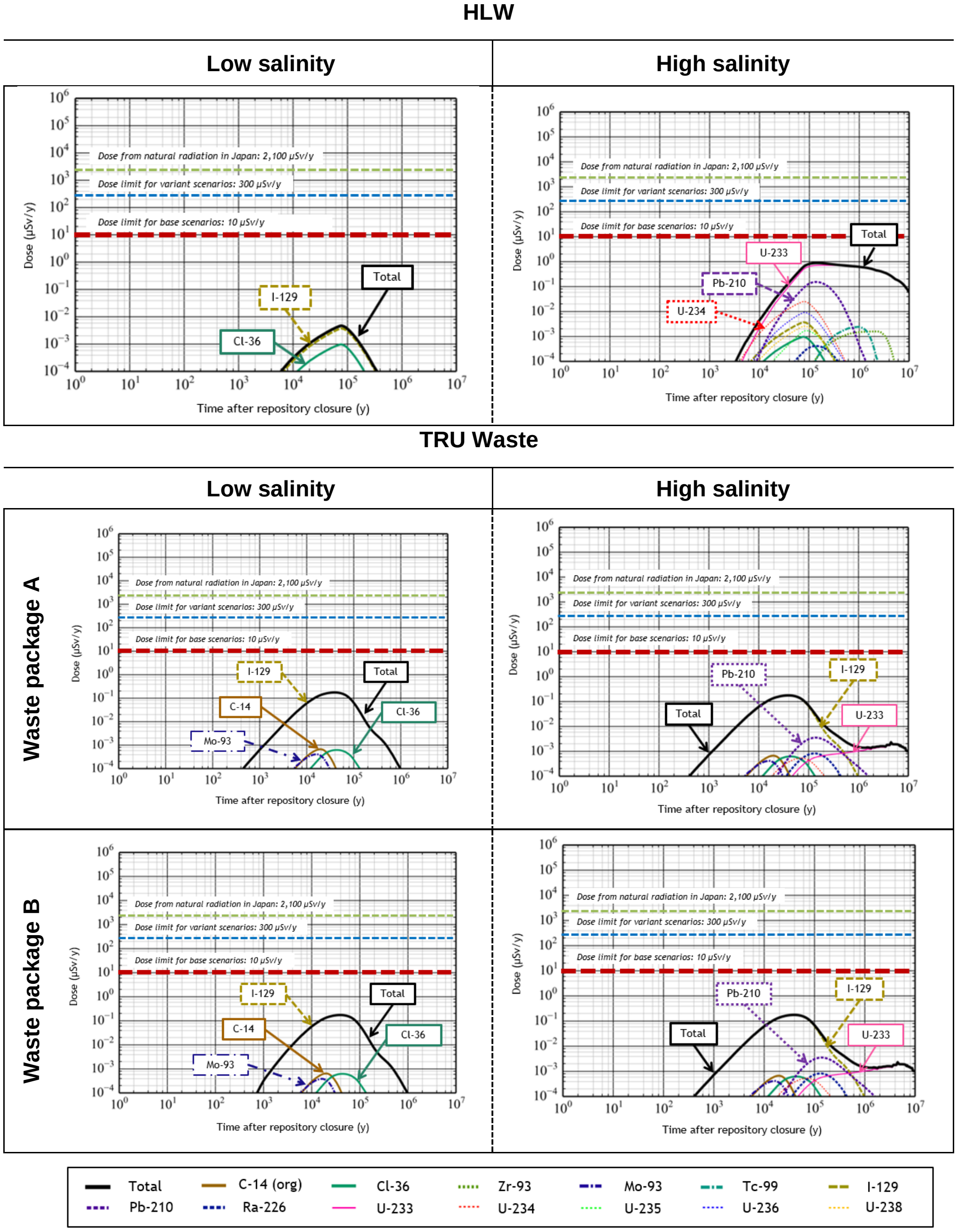


Figure 6.4-25 Doses and dominant RNs for Pre-Neogene repository (base case)

For the high salinity case, as for the Neogene sediments, up to about 40 ky after closure, TRU waste dominates releases. However, unlike the Neogene case, there is no early breakthrough of C-14 from Gr.4 and so I-129 from Gr.1 dominates throughout this time, since the modelled repository scale migration distance is much longer in the Pre-Neogene case. Thereafter, however, the situation is very similar to the Neogene case, apart from a longer release tail as explained above, with the maximum dose from the entire repository after about 130 ky (0.9 μSv/y), predominantly due to U-233 from HLW. This is again due to the high carbonate concentration of this groundwater (47 mM). The explanation of the roles of decay chain daughters is also the same here.

As for the Neogene sediments, the dose contribution from Se-79 has become negligibly small for HLW. This can be explained by the sorption coefficient of Se-79 for the Pre-

Neogene sediments which is about 40 times higher than plutonic rock for the low salinity case and about 50 times higher for the high salinity case. In contrast to the Neogene sediments Se-79, is also negligible for the TRU waste since the modelled migration distance is much longer.

The RNs that control the initial breakthrough for TRU waste package A are Sr-90 and C-14 for plutonic rock and Neogene sediments, respectively. However, neither of them is significant for the Pre-Neogene sediments; only slightly earlier breakthrough of I-129. The fact that C-14 does not dominate for the Pre-Neogene sediments is due to the much longer modelled migration distance, allowing for decay of this RN. The insignificant contribution of Sr-90 is mainly due to a combination of pathlength and a sorption distribution coefficient set to be 25 times larger than that of plutonic rocks.

(iii) Summary of the base case results

In all base cases, the maximum value of the calculated radiation doses occurs within about 100 ky and lies below the target of 10 μSv/y (see Supporting Reports 6-24, 6-25, 6-26).

As noted, the models used are highly conservative in terms of their treatment of migration distances through the geosphere and the selection of key parameters impacting RN release and migration (solubility limits and sorption distribution coefficients). For TRU waste, assumed instantaneous release and the mixing tank model of the EBS introduces further conservatisms. The high salinity water chemistry assumed for the Neogene and Pre-Neogene sediments includes very high carbonate concentrations that are reflected in the modelled extremely high mobility of U.

For HLW, there is almost no difference between calculated doses for the H12V and PEM options, with dose maximum in the low salinity case < 0.1 μSv/y for plutonic rock and < 0.01 μSv/y for the sediments; these are significantly less than doses from TRU waste. Doses were greater for higher salinity water in the sediments, giving a maximam ≈ 1 μSv/y due to higher U mobility; in these cases, exceeding the TRU waste doses.

The RN with greatest contribution to the maximum dose in plutonic rocks is I-129, predominantly from TRU waste. Overall repository performance is little impacted by groundwater salinity or TRU waste package type, although there is a noticeable early breakthrough of low levels of Sr-90 and I-129 for waste package A. Although this is mostly the result of overly conservative assumptions as noted previously.

For the Neogene and Pre-Neogene sediments, I-129 from TRU waste is also the dominant RN for the low salinity groundwater. In the case of high salinity groundwater, U-233 (produced from decay of Np-237) from HLW dominates because of assumed greater mobility as a result of the high carbonate concentration. This RN peaks significantly above I-129 from TRU waste, which is insensitive to salinity. In addition, since Pb-210 was assigned zero sorption, it also has a relatively large contribution to the dose from HLW. Although again maximum doses are not altered by TRU waste package type, minor early releases from waste package A are noticeable – predominantly C-14 in the Neogene case and I-129 for Pre-Neogene sediments.

It is clear that, in order to meet the goal of more realistic modelling to support comparison of different site/repository design options, major improvement is needed to reduce model simplifications and conservative/over-conservative data used to allow for system uncertainties. This is discussed further in Chapter 7.

6.4.2 Dose evaluation for variant scenarios

(1) Radionuclide migration model and dataset

Here, the analysis conditions and the corresponding models and databases for evaluating the dose based on the RN migration analysis will be described for the variant scenarios. The specification of these scenarios for the three host rocks are as presented in Tables 6.3-8 and 6.3-9.

For the variant scenarios, the dose constraint is 300 μSv/y, as described in Section 6.1.5 (2). However, a careful assessment of whether the likelihood of these scenarios are sufficiently low to warrant use of this constraint has not yet been done. The dose evaluation results of these cases are discussed by extracting the maximum value and time of occurrence from the calculated dose curve for each, in order to show differences from the appropriate base case. In the figures, analysis cases for low and high salinity groundwater are marked with the letters L and H, respectively. In addition, in order to associate each analysis case with the results in the figure, they are numbered as shown in Table 6.4-7. Background for setting conditions of RN release and migration modelling and selection of required parameters for each analysis case is summarised in Table 6.3-10.

As mentioned in Section 6.4.1 (5) for the base case, doses for the variant scenarios are calculated from use of the same simple dose conversion factors. Furthermore, for HLW, there was no significant difference in the handling of H12V and the PEM analyses, even taking into account differences in the geometry, since the calculation results are almost the same (Supporting Reports 6-24, 6-25, see 6-26).

For analysis case No. 2, the variant case is considered only for HLW, and for analysis cases Nos. 3 to 5, the variant case is considered only for TRU waste. In calculating the dose due to the whole repository in these analysis cases, the dose in the variant case is summed with the dose in the base case, where the variant case is not taken into account. For example, in the case of analysis No. 2, the dose for the whole repository is calculated using the dose in the variant case for the HLW repository and the dose in the base case for the TRU repository.

Table 6.4-7 Analysis cases and corresponding numbers

No.	Name of analysis case (see Table 6.3-10)	Analysis conditions (model and dataset)
1	Base case	Section 6.4.1 (2) to (6).
	Variant case	
2	Increase in glass dissolution case	Ten times the glass dissolution rate of the base case (see SR 6-13).
3	Increased corrosion of TRU Gr.2 case	Increased corrosion rate relative to the base case for zircaloy hulls (x9) and stainless-steel end pieces (x 14) (SR 6-13).
4	Uncertainty in structural frame degradation case	The hydraulic conductivity of the structural framework is set that of sand after repository closure.
5	Nitrate plume impact case	The impact of nitrate from TRU Gr.3 is defined as- • Plutonic rocks: For the TRU waste repository, the nitrate plume impacts RN migration at near field scales and repository scales. • Neogene sediments: For TRU waste Grs.1, 2 and 4LD and HLW, it is assumed that the nitrate plume affects the host rock at the repository scale. • Pre-Neogene sediments: For the TRU waste repository, the nitrate plume impacts RN migration at near field scales and repository scales.
6	Fracture connectivity in host rock case	Assuming higher facture network connectivity (see Appendix Figures 4 to 7).
7	Lower sorption in buffer case	Set sorption distribution coefficient values lower than the average value (see SRs 6-19 and 6-20, Appendix Tables 15 to 17).
8	Increased diffusivity in buffer case	Set effective diffusion coefficient values higher than the average value (see SR 6-19 and Appendix Tables 12 to 14).
9	Lower sorption in host rock case	Set sorption distribution coefficient values lower than the average value (see SR 6-22 and Appendix Table 21 to 23).
10	Increased diffusivity in host rock case	Set effective diffusion coefficient, values lower than the average value (see SR 6-20 and Appendix Tables 18 to 20)
11	Thermal increase in solubility case	Set solubility limit 100 times greater than the base case (see SR 6-17 and Appendix Tables 9 to 11)
12	Uncertainty in thermodynamic data case	Set higher solubility limits based on thermodynamic calculations considering other limiting solid phases (see SR6-17 and Appendix Tables 9 to 11)

(2) Plutonic rock (see Supporting Report 6-24)

The results of calculated total repository dose maxima for the variant cases listed in Table 6.4-7 for plutonic rock are summarised in Figure 6.4-26.

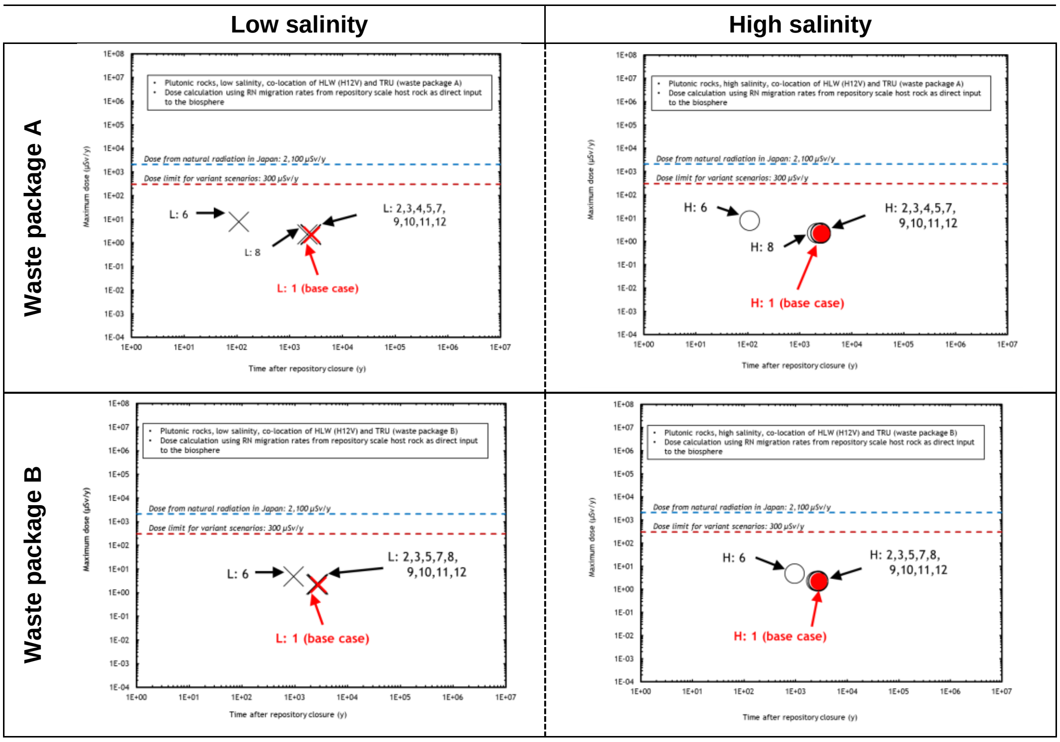


Figure 6.4-26 Total repository maximum dose and time of occurrence calculated for plutonic rocks (Note that case No. 4 is not applicable for package B)

These are presented separately for the two groundwaters and TRU waste package options considered.

It is clear that, in all cases, dose maximum is lower than the constraint value of 300 μSv/y. Regardless of differences in groundwater chemistry or TRU waste packaging, the maximum dose results from I-129 from TRU waste Gr.1 with no significant difference from the base case (1), with the single exception of case No. 6 (Fracture connectivity in host rock).

For case No. 6 and TRU waste package A, the maximum dose appears 100 y after closure and its value is about 7 μSv/y, predominantly due to Sr-90 derived from TRU waste Gr.3.

In this case, the transmissivities in multi-channel model are increased by an order of magnitude compared to the base case, resulting in higher groundwater flow velocity. For Sr-90, nitrate contained in Gr.3 results in a low sorption distribution coefficient for the host rock that, when combined with a very high initial inventory and the high groundwater flow rate gives the high and early maximum dose. As described in Section 6.4.1 (7) (ii) (a), in the RN migration analysis for Gr.3, an excessively conservative RN migration analysis model, in which the RN is instantaneously eluted from the waste, is used. A more realistic assessment of when waste could realistically contact groundwater and accounting for slow leaching of the bitumen matrix would certainly remove this artefact.

In the case of waste package B, for case No. 6, the maximum dose of 5 μSv/y is reached about 1 ky after closure, with I-129 from Gr.1 the dominant RN. The peak appears earlier than the base case and is slightly higher due to fast transport and less dispersion of this non-sorbing RN. Here, there is no significant contribution from Sr-90, due to decay of 10 half-lives (a factor of over 1000) before loss of containment at 300 y.

Figure 6.4-27 shows the maximum value of the dose and the timing of its occurrence separately for HLW and TRU waste. Variant cases related to HLW are No. 2 and Nos. 6 to 12, as listed in the Table 6.4-7. For the case of TRU waste, analysis cases Nos. 3 to 12 are relevant.

Although the maximum dose of the HLW variant cases has little impact on the total dose from the entire repository, these can be compared with the base case to show that that there are impacts in cases No. 2 “glass dissolution rate uncertainty”, No. 6 “Fracture connectivity in host rock” and No. 9 “Lower sorption in host rock”. Although case No. 2 gives an earlier peak arrival time, increases in dose maximum are larger for cases Nos. 6 and 9 but, at most, only about an order of magnitude.

The RN dominating the maximum dose in the base case was Se-79 (see Section 6.4.1 (7) (ii) (a)), but the maximum dose for case No. 2 results from I-129. This is because the glass dissolution rate is set to 10 times the base case and I-129 is treated without a solubility limit. In contrast, since Se-79 concentration in the source term is controlled by solubility, the release rate from the EBS is limited even when the glass dissolution rate increases.

Analysis cases No. 6 and No. 9 both show profiles of RN release similar to the base case (Figure 6.4-22), with Se-79 dominating the dose peak.

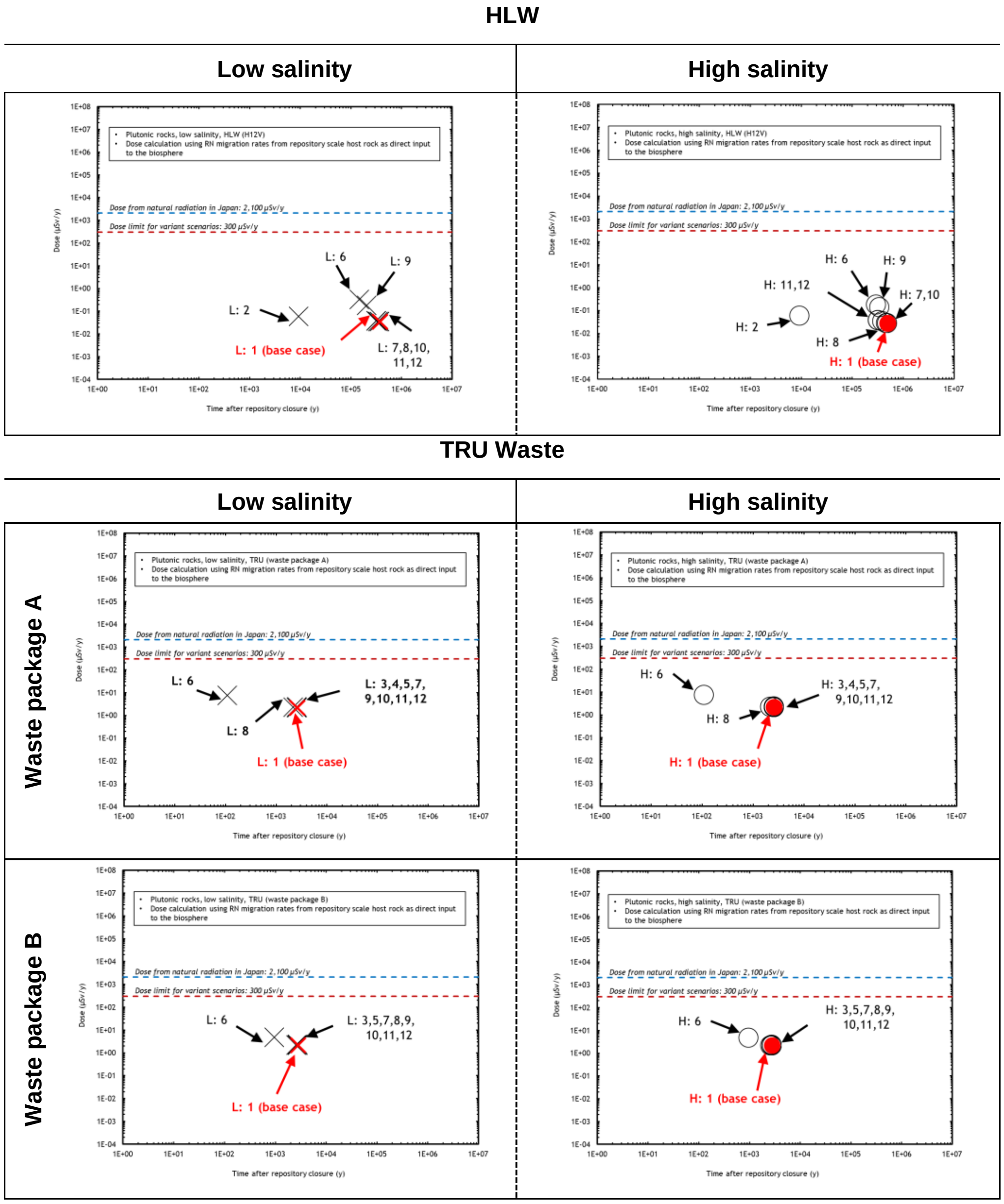


Figure 6.4-27 Separated HLW and TRU waste maximum dose and time of occurrence calculated for plutonic rocks (Note that case No. 4 is not applicable for package B)

For analysis case No. 6, the hydraulic conductivity of the host rock multi-channel model is increased by an order of magnitude compared to the base case (see Table 6.3-10, Appendix Figures 1 and 4), which implies that the transfer rate of RNs to the biosphere increases. As a result, the dose is higher than in the base case, but this effect works the same way for all the RNs. Therefore Se-79 will continue to dominate the maximum dose. Also, in the variant case No. 9, as shown in Appendix Table 20, the sorption distribution coefficient of Se-79 on host rock is reduced, and Se-79 becomes even more dominant in terms of the maximum dose.

Based on the above analysis, the only uncertainties that impact overall performance for HLW are associated with the long-term dissolution rate of the glass and sorption/fracture network characteristics. Even though the variant case is very pessimistic, better characterisation of glass dissolution will increase safety case robustness as this directly scales with the release from the EBS for the most mobile, highly soluble RNs that dominate dose.

Host rock characteristics will be very site specific but, given the key role of RNs such as Se-79, it is important to continue to improve the knowledge base on the release and transport properties of RNs that are determined to significantly contribute to assessed doses.

For TRU waste, the maximum dose and the timing of its occurrence for both waters and package types are little affected by any of the variants except No. 6, as discussed above for the total repository dose. Also discussed above are the impacts of the 2 different waste packages for this variant.

For the TRU waste, the variant cases demonstrate the importance of RN release and migration model assumptions and parameters for the EBS and geosphere, together with the impacts of perturbations – especially that from the nitrate plume. There is thus a clear need to make the repository migration model more realistic in order to assess what issues identified (e.g. role of longer-lived waste packages on containment of high inventory/short half-life RNs) are real (and should be a focus for future R&D) and which are artefacts of current model simplifications.

(3) Neogene sediments (see Supporting Report 6-25)

The results of calculated total repository dose maxima for the variant cases listed in Table 6.4-7 for Neogene sediments are summarised in Figure 6.4-28. These are presented separately for the two waters and TRU waste package options considered. It is clear that, in all cases, dose maximum is lower than the constraint value of 300 μSv/y.

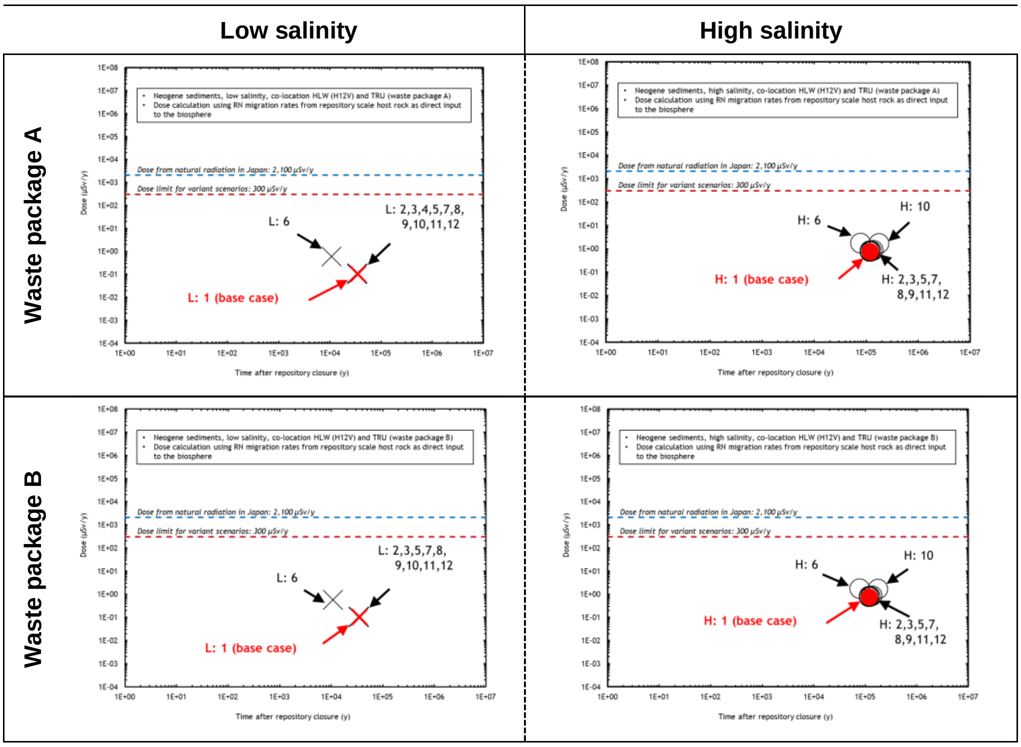


Figure 6.4-28 Total repository maximum dose and time of occurrence calculated for Neogene sediments (Note that case No. 4 is not applicable for package B)

For both groundwaters, the maximum dose and its appearance time for the two TRU waste packages are almost identical.

In the case of low salinity groundwater, as for plutonic rock, only variant case No. 6 causes a significant divergence from the base case, resulting in a higher dose peak (by about an order of magnitude) at an earlier time (about 10 ky). Again, this is derived from I-129 in Gr.1. As for the plutonic case, No. 6 increases the transmissivities in the multi-channel model by an order of magnitude compared to the base case (Table 6.3-10 and Appendix Tables 2, 5 and 7), resulting in a higher groundwater flow velocity and thus earlier breakthrough of I-129 with less dispersion.

In the case of high salinity groundwater, variant cases No. 6 and No. 10 (increased diffusivity in host rock) both cause slight deviations from the base case. It can be noted that the effect of the higher hydraulic conductivity of the host rock is smaller than the low salinity case, where I-129 is the dominant RN.

For variant No. 6, the maximum dose is derived from the HLW repository, as for the base case (see Section 6.4.1 (7) (ii) (b)). This is also due to U-233, which has a maximum dose about 2 times higher than that for the base case. As explained previously, the reason why U-233 dominates the dose over long times for the base case is explained by continuous ingrowth from its parent Np-237, which will remain in the buffer and rock for long timescales due to its low solubility and high sorption.

For variant case No. 10, Pb-210 derived from TRU Gr.4 is the dominating RN. The reasons for this RN having such a large contribution were discussed previously, with the lower rock diffusivity assumed for variant case No. 10 resulting in a dose contribution about two times higher than for the base case, which then slightly exceeds that of U-234. This is due to the importance of matrix diffusion for retarding non-sorbing RNs, which is reduced in this variant.

Figure 6.4-29 shows the maximum value of the dose and the timing of its occurrence separately for HLW and TRU waste. Again, variant cases related to HLW are No. 2 and Nos. 6 to 12 as listed in the Table 6.4-7. For the case of TRU waste, analysis cases Nos. 3 to 12 are relevant.

For HLW, as for plutonic rock, cases No. 2 and No. 6 show some divergence from the base case in low salinity water, although here the impacts on both arrival time and maximum dose are less. The RN that dominates the maximum dose is I-129, as in the base case, and the explanation is as for plutonic rock. For high salinity groundwater, only variant case No. 6 deviates from the base case, but only to a small extent, with both the dominant RN (U-233) and its explanation being the same. Plutonic rock comments on uncertainty reduction thus also apply here.

For TRU waste, in low salinity groundwater, the variants do not deviate from the base case except for analysis case No. 6. In terms of the dominant species, this is I-129 in all cases. The impact of increased conductivity on migration of this non-sorbing RN is as discussed above. For high salinity conditions, variants No. 6 and 10 show significant differences in maximum dose and time of occurrence, with very minor increases in maximum does also for variants No. 11 “Thermal increase in solubility case” and No. 12 “Uncertainty in thermodynamic data case”. For variant No 6, this is directly equivalent to the low salinity case. For variant case No. 10, the peak is due to Pb-210 results from Gr.4 as discussed for the entire repository above.

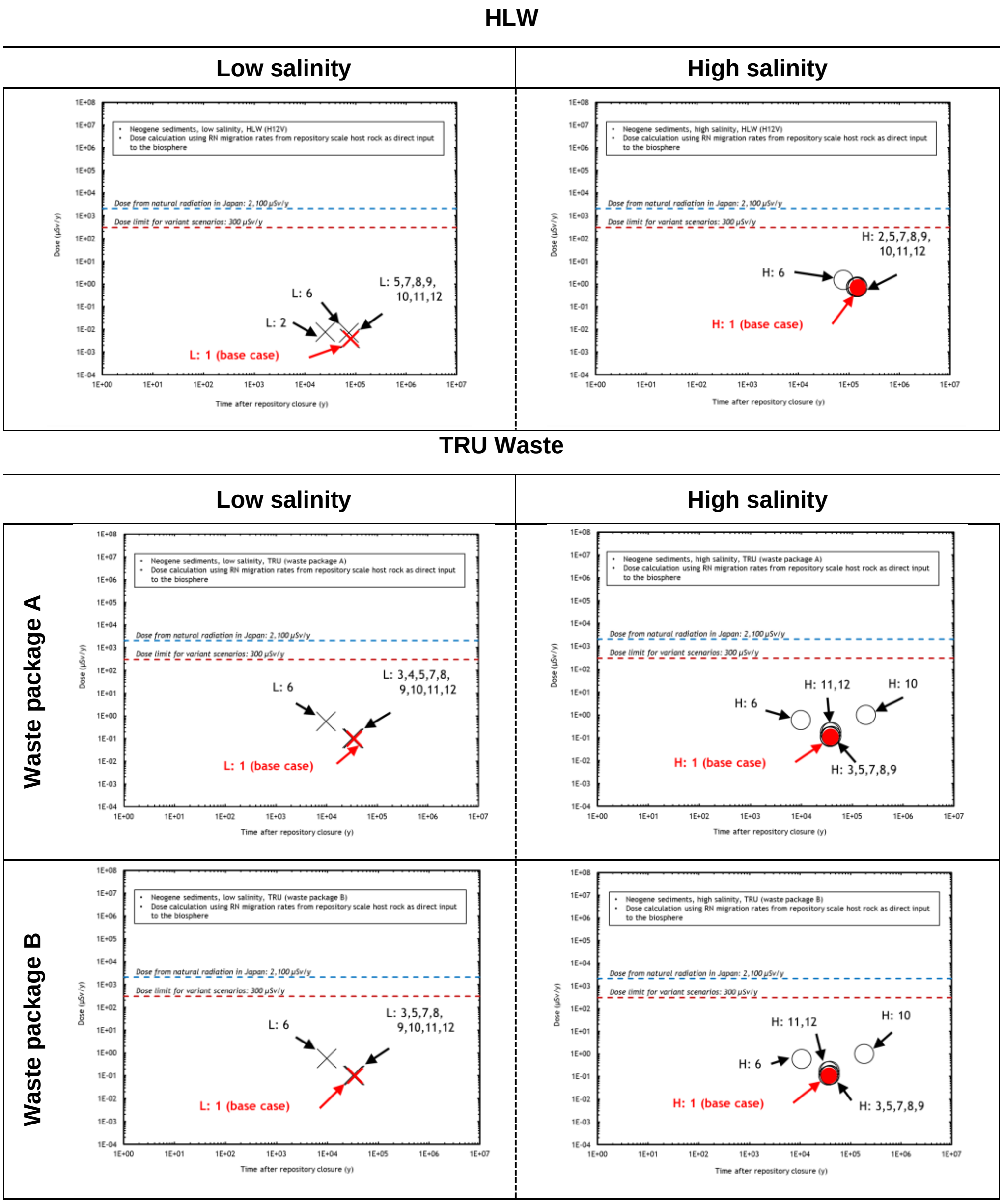


Figure 6.4-29 Separated HLW and TRU waste maximum dose and time of occurrence calculated for Neogene sediments (Note that case 4 is not applicable for package B)

Regarding variants No. 10 and 11, the dominant RNs are I-129 and Pb-210, with the contribution of the latter increased sufficiently to give a notably higher total dose. The increased dose from Pb-210 results from increased migration rate of its parent Th-230, due to higher solubility and decreased sorption.

In terms of reducing impacts of uncertainties, in addition to the points noted from assessment of the TRU variants for plutonic rock, the unexpected domination of releases of Pb-210 from TRU would merit R&D to support models and databases required for more detailed assessment of the treatment of migration of the actinide decay chains, especially for waters with high carbonate concentrations.

(4) Pre-Neogene sediments (see Supporting Report 6-26)

The results of calculated total repository dose maxima for the variant cases listed in Table 6.4-7 for Pre-Neogene sediments are summarised in Figure 6.4-30. These are presented separately for the two waters and TRU waste package options considered. It is clear that, in all cases, dose maximum is lower than the constraint value of 300 μSv/y.

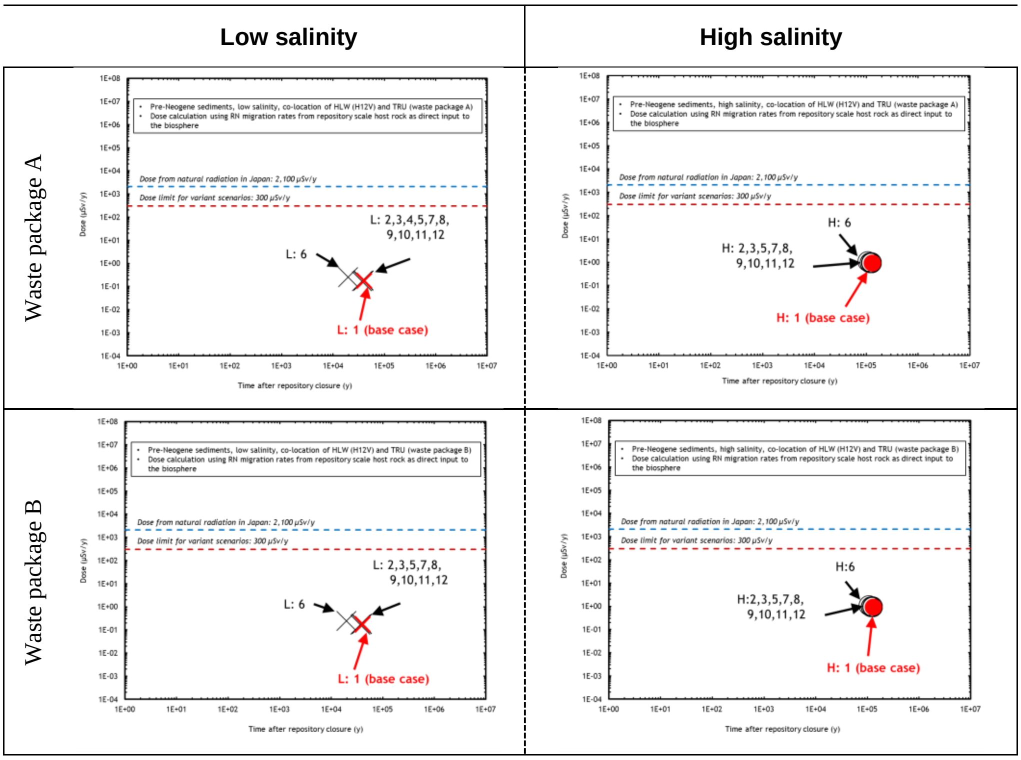


Figure 6.4-30 Total repository maximum dose and time of occurrence calculated for Pre-Neogene sediments (Note that case 4 is not applicable for package B)

Basically, it can be seen that the pattern is very similar to the Neogene host rock, with variant case No. 6 causing the only significant reduction of barrier performance for both waters and TRU package options for the same reasons. The extent of deviation is, however, less for the Pre-Neogene sediments and, for high salinity groundwater, the impact of variant case No. 10 is negligible.

Figure 6.4-31 shows the maximum value of the dose and the timing of its occurrence separately for HLW and TRU waste. Again, variant cases related to HLW are No. 2 and Nos. 6 to 12 as listed in the Table 6.4-7. For the case of TRU waste, analysis cases Nos. 3 to 12 are relevant.

For HLW, only analysis case No. 2 shows a significant impact for low salinity water, decreasing the peak arrival time but having little influence on peak dose. Case No 6 shows an influence for both waters, but it is extremely small. In all cases, the dominant RNs are as for the base case: I-129 in low salinity water and U-233 for high salinities with the same justification as discussed for Neogene sediments above and the same issues for reducing uncertainties for HLW as identified for the other two rocks.

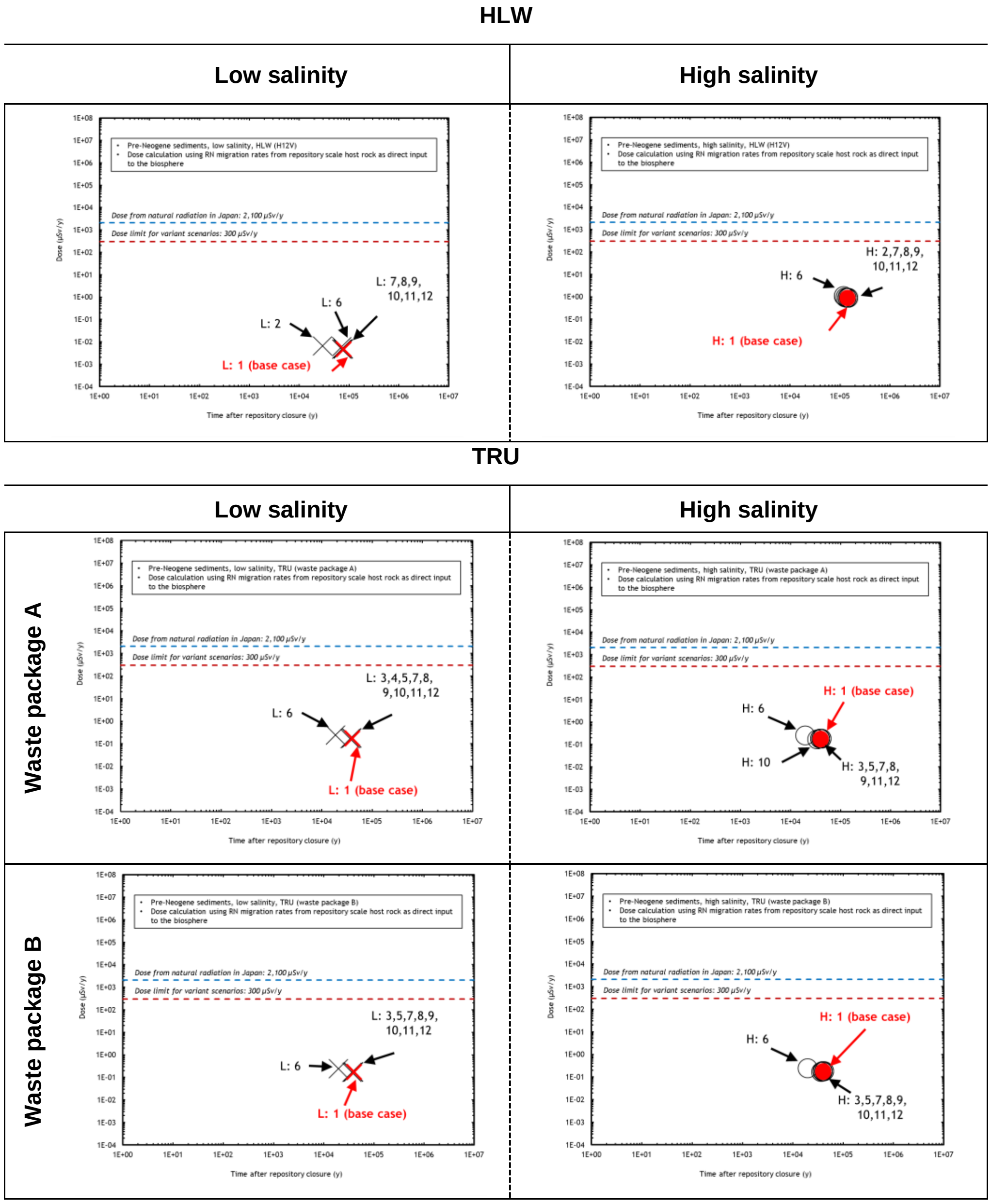


Figure 6.4-31 Separated HLW and TRU waste maximum dose and time of occurrence calculated for Pre-Neogene sediments (Note that case No. 4 is not applicable for package B)

For both ground waters, the maximum dose and its appearance time for the two TRU waste packages are identical. As for the Neogene sediments, case No. 6 gives rise to earlier breakthrough of a higher dose maximum, but the degree of change is significantly less. The transmissivity distribution is not as wide compared with other rock types, which also means that the transmissivity increase for case No. 6 was not as large. Unlike the Neogene sediments, however, variant case No. 10 has no significant impact and hence it is more similar to the plutonic case. Issues for reducing uncertainties for TRU waste are basically as for plutonic rock.

(5) Summary of dose evaluation results for variant cases

For all variant cases studied, the maximum doses calculated for the total repository with both TRU waste package options and both groundwaters lie below the 300 μSv/y target. Indeed, the value of the maximum dose for variant cases did not change significantly from the value for the relevant base case (Section 6.4.1 (7) (ii)).

This lack of sensitivity to more conservative model assumptions and data used certainly reflects a combination of both the very simplified models that are used for the base case and the generally conservative approach to data selection there. Of particular note here are the models of instantaneous release into a mixing tank for the TRU EBS and selection of no solubility limits and zero sorption for RNs in the base case, where there are considered to be large gaps in laboratory data and/or supporting mechanistic models.

Despite such inherent constraints, evaluation of the variant cases enable to identify some areas where further work can be focused to reduce uncertainties and add robustness to the safety case, such as improving the knowledge base to support low dissolution rates of HLW glass; extending studies of releases from TRU waste matrices and retardation by EBS components to support more realistic source term models; and improving understanding of RN geochemistry, especially in the case of evolving perturbations from high pH cement leachate or nitrate, or extreme groundwaters with high carbonate concentrations. It is clear that the geological barrier performance is sensitive to the characteristics of the flow system, as highlighted for the cases of increased DFN connectivity or reduced diffusivity into the rock matrix. Apart from appropriate site-specific characterisation, the capabilities of RN transport models will need to be improved in order to capture the key features of real rocks, such as spatial variability. Finally, it was noted that the output of models of transport of actinide decay chains are difficult to interpret and hence improvement here should include not only better representation of the processes involved, but also improved transparency of their impacts to allow these to be tested more rigorously. These issues are discussed further in Chapter 7.

6.4.3 Evaluation of low probability perturbation scenarios

In this section, the concepts supporting evaluation models and parameters and the dose evaluation results for analysis cases for the low probability perturbation scenarios noted in Table 6.3-11 are outlined. A large uncertainty is involved in setting the state of the repository for such scenarios and hence it is stylised, with a focus on clarity of evaluation and assured conservatism - without consideration of how physically realistic it might be. This enables investigation of the robustness of the repository system and the dose obtained by the analysis performed may be drastically over-conservative. Therefore, results of the analysis cases should be compared to dose targets for such scenarios only with great care.

(1) New volcanism scenarios

(i) Concept of evaluation model

As described in Section 6.3.2 (3) (iii), in this analysis case, new volcanoes are assumed to develop on the back side of the volcanic front around 100 ky in the future. The stylised model assumes associated magma directly impacts the repository, as illustrated in Figure 6.4-32. It is understood that there could be other consequences from volcanoes, such as impacts due to geothermal water entering the repository, but these have not been analysed in this safety case.

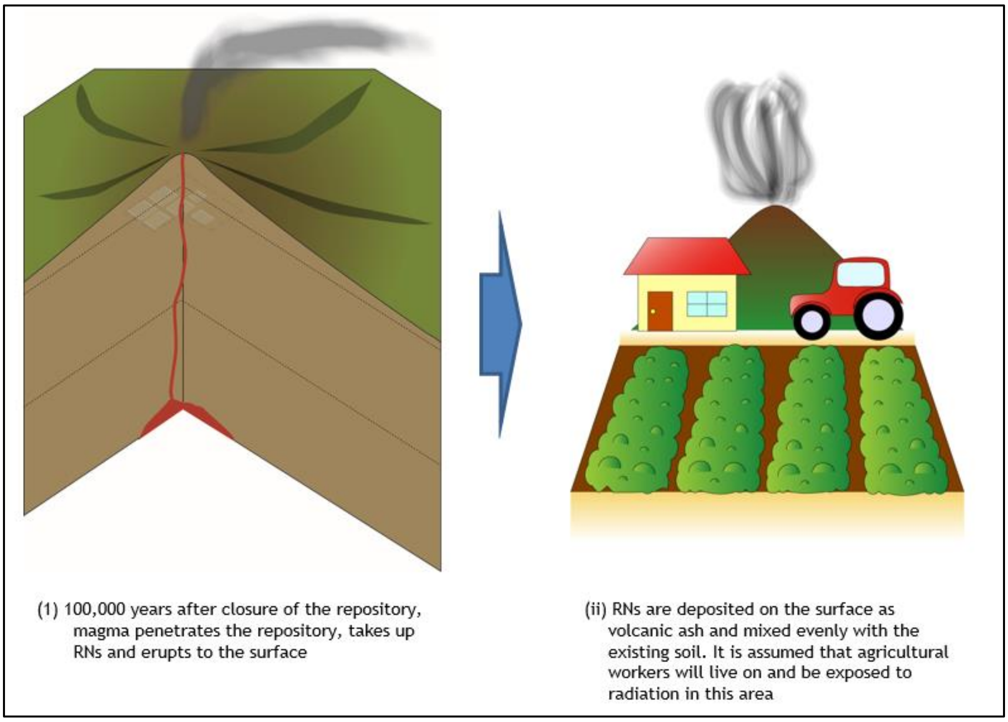


Figure 6.4-32 Conceptual model of new volcanism case

In this model, the following three points are assumed:

- For an appropriate site, 100 ky after closure is the minimum time for development of a new volcanic centre (for a site selected on the basis that no indicators of such a risk were seen): at this time, it is assumed that a conduit transporting magma from a deep chamber to a vent penetrates the repository footprint.
- RNs present in the region of this conduit (conduit area fraction) are taken up into the magma and released to the surface as ejecta (such as volcanic ash), which is then deposited in the vicinity.
- The amount of radioactivity incorporated into magma is defined by the inventory of RNs in the repository at that time, taking into account decay/ingrowth, but conservatively ignoring mobilisation by groundwater flow within the intervening 100 ky period.

Based on these assumptions, dose is evaluated as follows:

- Farmers are set as representative persons living in the fallout area; they cultivate soil that is homogeneously mixed with radioactivity falling out with volcanic ash. Dose is evaluated considering external exposure from soil, inhalation exposure of dust from soil, and oral ingestion exposure from eating local crops. Here, it is considered that mainly root vegetables are cultivated in the volcanic ash soil.

- For this evaluation model, differences in repository layout as a function of the host rock (as used in the evaluation of the base and variant scenarios) are taken into account.

(ii) Setting evaluation parameters

The following describes the setting of the required parameters for the model outlined above.

(a) Radioactive inventory in the repository

Assuming the occurrence of new volcano at 100 ky after closure, changes to the inventory for HLW and TRU waste due only to radioactive decay/ingrowth are considered, as given in Table 6.4-8.

Table 6.4-8 Radioactivity inventory used for new volcanism cases

Nuclide	HLW (Bq)
C-14	2.6×10^{7}
Cl-36	1.5×10^{13}
Se-79	1.0×10^{14}
Sr-90	0.0
Zr-93	2.8×10^{15}
Nb-93m	2.7×10^{15}
Nb-94	2.0×10^{11}
Tc-99	1.5×10^{16}
Sn-126	3.4×10^{14}
I-129	1.5×10^{12}
Cs-135	7.1×10^{14}
Cs-137	0.0
Pb-210	8.0×10^{12}
Ra-226	8.0×10^{12}
Ra-228	2.8×10^{7}
Ac-227	3.9×10^{11}
Th-228	7.8×10^{8}
Th-229	2.7×10^{14}
Th-230	8.1×10^{12}
Th-232	2.8×10^{7}
Pa-231	3.9×10^{11}
U-232	7.5×10^{8}
U-233	3.0×10^{14}
U-234	1.2×10^{13}
U-235	5.2×10^{11}
U-236	5.9×10^{12}
U-238	1.6×10^{12}
Np-236	5.9×10^{9}
Np-237	8.3×10^{14}
Pu-236	7.5×10^{8}
Pu-238	0.0
Pu-239	9.6×10^{14}
Pu-240	3.8×10^{11}
Pu-241	1.9×10^{11}
Pu-242	1.6×10^{13}
Pu-244	6.4×10^{6}
Am-241	2.0×10^{11}
Am-242m	0.0
Am-243	2.7×10^{12}

Nuclide	HLW (Bq)
Cm-243	0.0
Cm-244	0.0
Cm-245	1.9×10^{11}
Cm-246	5.2×10^{7}
Cm-247	4.3×10^{8}
Cm-248	1.1×10^{9}

Nuclide	TRU waste (Bq)
C-14	3.7×10^{9}
Cl-36	7.5×10^{12}
Co-60	0.0
Ni-59	3.8×10^{15}
Ni-63	0.0
Se-79	4.3×10^{12}
Sr-90	0.0
Zr-93	3.7×10^{14}
Nb-94	8.8×10^{13}
Mo-93	2.3×10^{6}
Tc-99	5.8×10^{14}
Pd-107	1.1×10^{12}
Sn-126	5.7×10^{12}
I-129	5.9×10^{13}
Cs-135	5.8×10^{12}
Cs-137	0.0
Pb-210	8.3×10^{12}
Ra-226	8.3×10^{12}
Ra-228	1.3×10^{7}
Ac-227	1.9×10^{11}
Th-228	1.3×10^{7}
Th-229	4.7×10^{12}
Th-230	8.4×10^{12}
Th-232	1.3×10^{7}
Pa-231	1.9×10^{11}
U-233	5.2×10^{12}
U-234	1.2×10^{13}
U-236	2.7×10^{12}
U-238	1.3×10^{12}
Np-237	1.4×10^{13}
Pu-239	2.2×10^{14}
Pu-240	1.3×10^{11}
Pu-241	8.0×10^{8}
Pu-242	1.5×10^{13}
Am-241	8.4×10^{8}
Am-243	1.7×10^{11}
Cm-244	0.0
Cm-245	8.0×10^{8}
Cm-246	0.0

(b) Spatial considerations

Based on the radioactivity inventory shown in Table 6.4-8, the dose was calculated for the H12V repository in plutonic rocks, as this is relatively compact. The release of RNs into the biosphere is calculated from the inventory in the area of the HLW repository or intersected by the conduit divided by the volume of ejecta. This gives the radioactivity concentration of the RN in the ash that reaches the surface. To set the area of the volcanic conduit and the volume of the volcanic eruption, reference eruptions selected in Supporting Report 3-34 were used (see Table 6.4-9).

Table 6.4-9 Conduit areas and ejecta volumes used for evaluation

Name	Conduit area (km^2)	Ejecta volume (km^3)
Mikugawa caldera	0.2	1×10^2
Komochi-yama	7×10^{-2}	10
Kamitakara	4	40
Unzen-dake	2×10^{-2}	0.2

(c) Biosphere evaluation parameters

External exposure, inhalation exposure, and oral ingestion exposure are assessed as the reference farmer`s exposure routes. Stylised biological and lifestyle characteristics [96] were used to calculate dose due to external exposure and inhalation of dust. Furthermore, assuming that root vegetables were cultivated in this soil, doses from internal exposure resulting from consumption of local crops [97] were calculated (see Supporting Report 6-27 for details).

(iii) Results and discussion

The evaluation of the worst case stylised new volcano scenario resulted in a dose of 0.09 mSv/y which is well below the dose target (20-100 mSv) for the first year and also the dose target thereafter (1-20 mS/y), as specified for low probability scenarios.

According to the ITM-TOPAZ method [33] [34] [35] [36], as described in Chapter 3, the probability of such a new volcano generation can be derived based on expert judgment. According to this approach, the probability of occurrence greatly depends on regional features, but if sites within 15 km radius from Quaternary volcano centres are avoided, in the region of Tohoku the probability is calculated to be ~ 10^{-6}/y/100 km^2 (Supporting Report 3-34). Using this, the associated risk for the above dose (see Section 6.1.5 (2)) and the repository footprint is about 1×10^{-12}/y, which is far below the internationally recommended risk constraint value 10^{-5}/y.

(2) Fault extension scenarios

In this analysis case, it is assumed that, over a long period of time, a major fault gradually extends until it impacts the repository and forms a short circuit from the near field to the biosphere. Since the impact of such a migration path depends on the layout of the repository and the geological environment, the analysis considers both model waters defined for plutonic rocks, Neogene and Pre-Neogene sediments. In addition, the H12V option is assumed for the HLW repository, with the conservative assumption that the entire RN inventory remains in the EBS, as for the new volcanism case. See Supporting Report 6-28 for details of models and parameters.

(i) Conceptual model

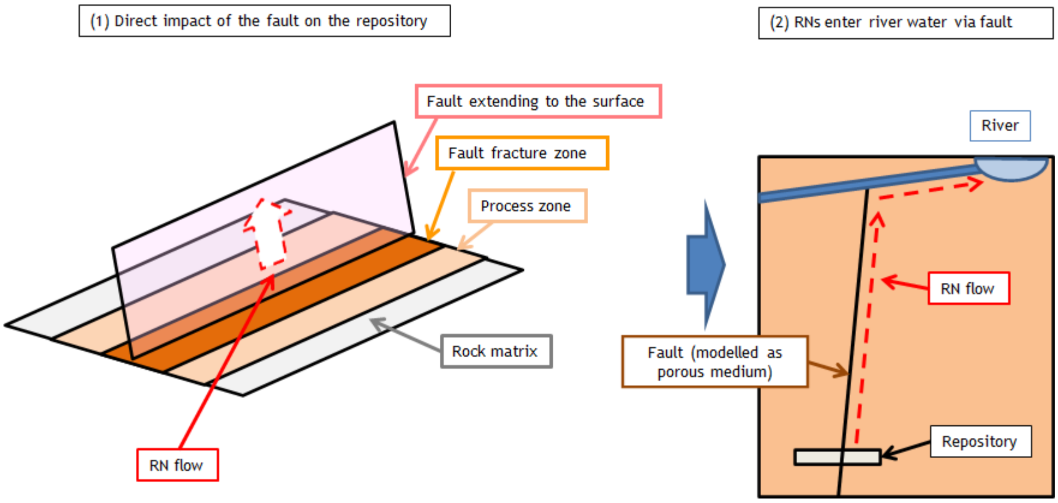


Figure 6.4-33 Concept of fault extension scenario

The scenario concept to be captured by the evaluation model is shown in Figure 6.4-33.

In this model, the following assumptions are made:

- Faulting starts at great depth (6 to 20 km) and then gradually extends to the surface.
- An extension of this major fault directly hits a disposal panel at a certain time after repository closure.
- The fault zone and associated process zone gradually increase in size as the fault repeatedly activates (see Supporting Report 3-35); so these do not develop in one fault movement event [66]. In the evaluation, however, an extreme condition in which the fault zone and the process zone result from a single event is assumed.
- For parts of the repository located in the fault plane/fracture zone, all safety functions of the EBS and the geological environment are lost. For parts located in the process zone, the groundwater flow velocity of the rock rises, so the safety function of reducing RN migration is degraded.
- All RNs eluted in groundwater from waste within the fault zone move to the surface environment via flow in the fault.
- The RN migration path to biosphere ends with releases to the GBI equivalent to that for the base case scenarios (see Section 6.4.1 (6)). Assuming that a breccia zone with structures typical of existing faults is present (see Supporting Report 6-28), a RN migration model with faults handled as a porous medium in which sorption of RNs occurs is utilised, as for the regional scale base case (see Section 6.4.1 (5)).

(ii) Setting parameters

(a) When the event occurs

It is expected to take a very long time until a fault extension directly hits the repository for the given siting criteria, but it is difficult to specify the minimum time needed. Considering the great uncertainty regarding the timing when such a scenario occurs, as for H12 possible times 1 ky, 10 ky and 100 ky after closure are considered.

(b) Characteristics of the fault extension

With regard to the size of the fault that reaches the repository and affects its safety functions, the depth of the fault is set to 6 to 20 km as noted above. Assuming that an earthquake occurs from this seismogenic layer, it was decided to target a 20 km scale fault that could conservatively generate earthquakes up to around M7.0.

In accordance with Supporting Report 3-35, a fault zone having a width of 100 m on each side of the fault plane and a process zone with a width of 220 m outside the fault zone was set for the calculations.

Depending on the location and shape of the fault, the number of waste packages impacted will be different. Since it is not possible to predict how this fault hits the repository without site-specific information, the resultant dose from HLW and TRU waste is calculated by extremely conservative, stylised scenarios as shown in Table 6.4-10.

Table 6.4-10 Stylised fault representation

Waste type	Assumptions
HLW	• It is assumed that a linear fault occurs at a position where it intersects the largest number of waste packages for each panel of the reference repository (see Supporting Report 6-28). Table 6.4-11 shows the number of packages impacted by the fault plane, fault zone and process zone. • The dose is first calculated for intersection with one panel and then dose from the entire HLW repository is obtained by multiplying this dose by the total number of panels. For the Pre-Neogene repository, since the number of tunnels is different for each panel, the dose is calculated for the panel with the greatest number of waste packages, and this dose is multiplied by the number of panels.
TRU	• Because it is difficult to define how the fault hits the repository, it is conservatively estimated that all TRU waste vaults are directly hit by the fault.

Table 6.4-11 Impact of defined fault on HLW disposal layouts

Host rock	Impact per panel (number of waste packages)			Number of panels
	Fault plane	Fault zone	Process zone	
Plutonic	139	2780	3750	6
Neogene	131	2100	4450	6
Pre-Neogene	250	3000	1750	8

(c) Characteristics of RN migration pathways

As outlined in section (i), and further detailed in Supporting Report 6-28, the modelling of the EBS is different for different parts of the fault, as indicated in Figure 6.4-33. For waste packages located in the fault plane, all safety functions of the EBS are lost and all RNs in the waste are assumed to be instantaneously released into the fault. Waste packages located in the fault zone are assumed to lose the buffer safety functions but, for HLW, slow release from the glass matrix would remain. The EBS is assumed to be intact in the fault process zone, but the groundwater flow velocity of the EDZ increases.

The parameters set for the characteristics of the stylised fault RN migration path are shown in Table 6.4-12 for the three representative rock types.

Table 6.4-12 Parameters for RN migration analysis in the fault

Parameters	Plutonic rocks	Neogene sediments	Pre-Neogene sediments
Hydraulic gradient	0.05	0.06	0.05
Hydraulic conductivity (m/s)	1.0×10^{-5}		
Porosity	0.1	0.3	0.5
Rock density (kg/m^3)	2700		
Path length (m)	700	200	700
Dispersion length (m)	70	20	70
Sorption distribution coefficient (m^3/kg)	Appendix Table 21	Appendix Table 22	Appendix Table 23

The migration distance is based on the repository depth, hydraulic gradients are the same as the base case and fault hydraulic conductivity is conservatively set to the equivalent of sand.

(iii) Results and discussion

The results of the dose evaluation are shown in Table 6.4-13 for each model water, the three representative host rocks and the different assumed times at which faulting occurs. Despite the very conservative assumptions described above, the sum of the doses from HLW and TRU waste is a maximum of 14 mSv/y for the Neogene sediments (for both groundwater types).

Table 6.4-13 Maximum doses calculated for HLW and TRU waste fault extension analysis cases (for different occurrence times)

Host rock	Model water (salinity)	Maximum dose (mSv/y) and dominant RNs					
		HLW			TRU waste		
		10^3 y	10^4 y	10^5 y	10^3 y	10^4 y	10^5 y
Plutonic	Low	0.3 Pu-239	0.2 Pu-239	0.1 Np-237	4 I-129	4 I-129	4 I-129
	High	0.3 Pu-239	0.2 Pu-239	0.1 Np-237	4 I-129	4 I-129	4 I-129
Neogene	Low	0.1 Tc-99	0.1 Tc-99	0.08 Tc-99	14 I-129	14 I-129	14 I-129
	High	0.4 Tc-99	0.4 Tc-99	0.7 U-233	14 I-129	14 I-129	14 I-129
Pre-Neogene	Low	0.1 Tc-99	0.1 Tc-99	0.07 Tc-99	4 I-129	4 I-129	4 I-129
	High	0.9 Tc-99	1.0 Tc-99	2 U-233	4 I-129	4 I-129	4 I-129

In all cases the estimated dose is within the target range of 1 to 20 mSv/y for the low probability perturbation scenarios from the second year after the occurrence. For all three host rocks, the TRU waste dose is higher than that from HLW.

For HLW, the only EBS function is congruent dissolution from the glass matrix for packages located on the fault plane. With this release, the dominating RN changes for the different rocks and groundwater chemistry due to the differences in sorption distribution coefficients for the fault and the timing of event occurrence (due to radioactive decay and ingrowth). For TRU waste, the doses are dominated in all cases by I-129, for the same reasons as for the base case.

These results reflect the assumption that all RNs are confined in the waste until the fault directly hits, with elution of RNs commencing immediately thereafter, which is probably realistic for HLW up to at least 10 ky, but conservative for TRU waste. The RN migration model and parameters used are as for the base case, with the same limitations and uncertainties as previously discussed.

For this scenario, a 20 km scale fault is assumed to have occurred in the area of the repository; the probability of such an event is ≈ 2.2×10^{-7}/y (see Supporting report 3-35). Converting the maximum dose of 14 mSv/y (for the Neogene sediments) into a radiological risk (see Section 6.1.5 (2)) and multiplying this by the probability of occurrence, the total risk is calculated to be 2×10^{-10}/y, far below the risk constraint recommended by ICRP (10^{-5}/y). The dose calculation is considered to be extremely conservative and thus, even for such a stylised scenario, supports the conclusion that the repository concept is robust in the case of such a perturbation.

(3) Summary of results for low probability perturbation scenarios

For the low probability perturbations analysed, development of a new volcano or an extended fault that directly impacts the repository, even very pessimistic scenarios indicate that doses would not be unacceptably high and, when coupled to an assessment of likelihood of occurrence, risks are extremely small. Thus, it is concluded that, by selecting sites and designing the repository appropriately, long term safety of the repository would not be lost even if such low probability events should occur

6.5 Evaluation of inadvertent human intrusion scenarios

6.5.1 Development of human intrusion scenarios

In assessment of the safety of the repository after closure, future human activities that could impact barrier performance must be considered. The focus is entirely on actions that inadvertently or accidentally impact the repository, as opposed to any intentional operation specifically aimed at intruding into, or influencing the behaviour of, the repository, corresponding to the international consensus and guidelines on such treatment [2][29][38][42][98].

In Japan, as elsewhere, the risk of unintentionally impacting a repository is reduced by locating it below the depth at which human activities are common and siting it to avoid areas where there are underground resources with economic value that could be a motive for human activities (for example, [98][99]). Further, restrictive measures with respect to activities such as drilling will apply to the repository during the institutional control period after closure (e.g., [27] [42]), while records will be maintained to assure that such restrictions continue indefinitely[11] (e.g., [27][37]). Finally, there are arguments ([51][100]) that physical resistance to intrusion of the repository itself can be expected. For example, in the case of strong overpacks, these may resist intrusion by drilling until they are significantly degraded.

As also discussed in Section 6.1.5 (2) (iv), it may be argued that the probability that the safety functions of the repository will be significantly impaired by human intrusion may be considered to be small, but also extremely difficult to assess in any rigorous manner. Therefore, human intrusion scenario evaluations are considered in a similar manner to the evaluation of low probability perturbation scenarios, as discussed in Section 6.4.3: given inherent uncertainties, stylised scenarios aim to illustrating the robustness of the repository and show that no significant radiological impacts are to be expected.

In terms of handling human intrusion scenarios, various arguments have been made in international organisations and regulatory and implementing agencies (e.g., [101][102][103]). Through these discussions, it is clear that there is no strict scientific basis to predict human actions and the likelihood of future human intrusion. Therefore, the approach of developing stylised scenarios to confirm the robustness of the safety functions of the repository is widely accepted.

In this report, the specific methodology for developing human intrusion scenarios was also considered, with reference to the latest trends in Japan and abroad. Although human intrusion scenarios depend on site conditions, since such scenarios are considered for repositories in many countries, these are referred to directly to the extent possible.

(1) Setting requirements for building human intrusion scenarios (see Supporting Report 6-29)

The IAEA [2][38], ICRP [29][42], OECD/NEA [103] and the Nuclear Safety Commission [40] [104] discuss requirements relating to the development of human intrusion scenarios as follows:

1. Target actions that give direct disturbance to the repository.
2. Target actions that are expected to occur during the period after the repository is closed.
3. Focus on inadvertent human intrusion (do not consider intentional intrusion).
4. Measures against inadvertent human intrusion[12] should reduce its probability of occurrence.
5. Envisaged scenarios should be credible (plausible) and stylised based on current techniques and procedures that could lead to intrusion.

(2) Selection of relevant human intrusion actions (see Supporting Report 6-30)

In view of the above requirements, the actions to be considered in human intrusion scenarios are extracted from the NUMO FEP list (Supporting Report 6-4). As a result, “F1.4.5 Drilling activities” was selected whereas “F1.4.9 Water management (groundwater, surface

[11] In Japan, it is prescribed that records are permanently preserved by the Minister of Economy, Trade and Industry (Article 18, paragraph 2 of the Final Disposal Act).

[12] Drilling restriction measures and record preservation, location signs, depth of construction more than 300 m, avoiding economically important resources, etc.

water)”[13] and “F1.4.6 Mining and other underground activities” were discarded, as explained in Supporting Report 6-30.

According to a report that collated information on drilling in Japan [105], objectives are classified into five major areas: hot spring development; well development; academic research; resource exploration; and construction work. Most of the drilling carried out to depths of 300 m or more (minimum repository depth required by the Final Disposal Act) is aimed at hot spring development and resource exploration.

According to the Hot Springs Act in Japan, hot springs are defined as “hot water from the ground, mineral water, steam and other gases” which implies that springs containing a certain amount or more of dissolved substances, regardless of temperature, are treated as hot springs. Therefore, hot spring development can occur regardless of the regional setting. In terms of resource exploration, as maps of economically valuable mineral resources are used to exclude areas for consideration as potential sites, the likelihood of occurrence is considered to be small compared to drilling for hot spring development, while the degree of disturbance can be expected to be equivalent. From the above requirements 4 and 5, it was decided to evaluate the drilling for the purpose of hot spring development as a plausible human intrusion scenario in Japan.

(3) Stylised human intrusion considerations

In stylising the act of human intrusion, it is necessary to consider the timing of occurrence of the event, the radioactive inventory in the repository at that time, the location of intrusion, and the route of transfer of RNs from the EBS to the biosphere. These are set so as to satisfy the above requirements 1 to 5.

(i) Setting time of occurrence (see Supporting Report 6-31)

As in other countries, it is assumed that human intrusion does not occur during the period when institutional control is effective [31][44][51][99]. Thus, times of 200 y [99], 300 y [44] or 500 y [31] after closure have been taken as possible times when the institutional management period ends, which is taken as the earliest time for a human intrusion scenario.

In this report, the time when human intrusion occurs based on similar considerations for Japanese boundary conditions is also considered. In the safety regulations for medium depth disposal currently under development [106], an institutional control period of 300-400 y is assumed, allowing human intrusion scenarios to be considered immediately after this period. Similar assumptions for deep disposal were made. It is noted, however, that Japan has an extensive record of preservation of historical documents (e.g., the “Shōsōin documents” dating from AD 702 [107]). In light of such experience, it was decided to assume that human intrusion will occur 1 ky after closure, but consequences of human intrusion at 300 y after closure are also analysed. These times are not significantly different from those set in other countries.

In addition, it may be argued that there are cases where the timing of occurrence is being considered based on the idea that human intrusion does not occur during the period when the

[13] Water management (groundwater, surface water), including intake, reservoirs, dams and river management. N.B. This footnote is not included in the Japanese version of the report.

facility can be expected to have physical resistance. In Switzerland, for example, the reference disposal concept for both HLW and SF has a steel overpack with an expected lifetime of 10 ky (although Cu is an alternative option, with a minimum lifetime of 100 ky and expected lifetime of 1 My). The arguments for intrusion scenarios [51] depend on whether a borehole directly hits an overpack or not. If it does, no penetration of the overpack is assumed until it is extensively corroded. If drilling is between the overpacks, then releases occur after loss of containment (10 ky).

Based on this example, expected waste package resistance to drilling for a hot spring was compared. This allows setting the time of occurrence of the scenario based on when these are considered to have lost such physical resistance.

The time of loss of physical resistance of the HLW overpack is taken to be 35 ky after closure, i.e. much longer than the assumed time for loss of containment, since even then most of the steel would remain. The loss of physical resistance is assumed to be 18 ky in the case of a TRU waste package B (see Supporting Report 6-31). For TRU waste package A, since it has no top cover, no physical resistance can be expected. Incidentally, for the estimation of the amount of steel corrosion, a more realistic corrosion rate was used (overpack Section 4.4.1 (2) (iii) (a), TRU waste package Section 4.4.2 (2) (v) (b)).

(ii) Setting the intrusion location

For the designed repository layout, hitting a waste package with a borehole and subsequent penetration without this event being noticed by drillers is considered to have a very low probability. Based on the requirements described in Section 6.5.1 (1), however, the borehole is assumed to be drilled from the surface directly above the waste emplacement positions for either HLW or TRU waste.

(iii) Migration path and exposure routes (see Supporting Report 6-32)

For the human intrusion scenario, there is a possibility of exposure to both the intruder and the general public around the repository. In accordance with requirement 5 from Section 6.5.1 (1), with reference to the current use of boreholes for the purpose of hot spring development in Japan, a situation in which intruders and the general public are exposed was set as described below [105] [108] [109]. It is noted that some safety regulations in other countries do not require evaluation of dose to intruders [27].

(a) Driller exposure (worker exposure case)

Workers are exposed while drilling through the waste when material is transported to the surface together with the excavated spoil or by exposure from the core. Currently, with boreholes aiming at hot spring development in Japan, it is common to periodically observe the excavated spoil in order to understand the setting, with observation of bore core sometimes performed instead. In consideration of this, it is assumed that one of the workers is responsible for such observation of the spoil and/or core.

(b) General public exposure (borehole pathway case)

For the general public radiation exposure, the borehole was assumed to be backfilled after excavation, but provides a short circuit path between the repository and the biosphere. RNs thus released to a river via a near surface aquifer can result in doses from the utilisation of such water.

(4) Models and datasets used for dose evaluation (see Supporting Report 6-33)

(i) Radionuclide inventory

To evaluate doses for human intrusion, it is important to specify the inventory of RNs within the EBS at the time of occurrence. When the time of initiation of RN release from waste is shorter than the occurrence time, a part of the RN inventory is lost from the EBS; this acts to reduce the dose calculated. Here, from the viewpoint of conservative evaluation, it is assumed that the original RN inventory will remain within the waste matrix, with correction only for the effects of radioactive decay/ingrowth.

In addition, for the borehole pathway described in Section 6.5.1 (4) (iii), it is assumed that all RNs released in aqueous solution will migrate to the surface through the borehole. If the borehole penetrates the waste package, it is conservatively assumed that the waste matrix is completely destroyed and all RNs are instantaneously released into the borehole.

(ii) Worker exposure case

In the dose evaluation model of this case, one worker performs drilling work around the borehole. The drilling spoil tank is located at a fixed distance from the borehole, as is the temporary store of drill cores. The worker may be externally exposed to radiation either from observation of the drilling spoil or by observation of the drill core. Inhalation of dust and internal exposure by oral intake is also considered. Only exposure to the driller is considered in this scenario, potential doses that may occur later, e.g., when analysing and mapping the core or from subsequent use of the drilling spoil, are not considered.

The RN inventory contained in spoil or drill core is that of the waste matrix through which the borehole penetrated. For HLW, the H12V option was considered. For TRU waste, a range of different waste groups and package emplacement designs are included. In this case, based on its highest potential radiotoxicity, Gr.4H is conservatively selected for assessment.

In the case where representative information is available, such as the specifications of the equipment used in drilling for the purpose of hot spring development (e.g. the diameter of the borehole etc.), this is used in the dose evaluation model. For parameters that are highly dependent on the working environment, such as dust concentration and core observation time, values are taken over from IAEA reference documents (e.g. [110]).

(iii) Borehole pathway specification

After hitting the waste, it is assumed the hole is backfilled with a material such as cementitious grout; to model RN migration, the backfilled borehole is represented as a porous medium. Abandoned open boreholes were not considered, since backfilling boreholes is the normal practice in Japan.

For HLW, dose assessment assumes one package penetrated and, for TRU waste, one disposal tunnel for each waste group.

With respect to the RN transfer parameters in the borehole, due to uncertainty, conservative values for the infilled hole were selected. For example, a high hydraulic conductivity (1 x 10^{-5} m/s) similar to sand is set together with an upward hydraulic gradient. Since the gradient in the borehole depends on the specific conditions of the geological environment and surface topography, it is difficult to set in a generic manner, so values equivalent to that of the representative host rocks[14] are set (see Section 6.4.1 (2) (v) (a) 3). With regard to the sorption of RNs on borehole infill, it is assumed that leaching of it does not proceed to a significant extent for the timescale considered (Supporting Report 6-16), and hence sorption distribution coefficients were chosen to be the same as those used in the base case for the cementitious vault infill.

The length of the borehole migration path was defined by the repository depth minus the thickness of an assumed permeable surface cover. Dose was calculated by multiplying the release rate of RNs by the dose conversion factors used in the base case (see 6.4.1 (6) (iii)).

6.5.2 Results and discussion

For the worker exposure case, assuming that the work end or someone notice an abnormality within one year after the start of drilling the applied dose target is 20 to 100 mSv over a 1- year period (see Section 6.1-6). However, in the case of borehole releases impacting the general public, since there is a possibility that these will continue to be affected for a long time after intrusion occurs, in the first year the dose target is 20 to 100 mSv. From the second year onwards, comparison was made with a target of 1 to 20 mSv/y.

Table 6.5-1 summarises results for the two analysis cases (see Section 6.5.1 (4)), showing the maximum value of the calculated radiation dose and its time of appearance.

In the worker exposure case, the exposure doses are highest for all rocks when the intrusion time is 300 y from the closing of the repository (50 to 60 mSv). Nevertheless, the dose falls within the target range of 20 to 100 mSv. In this analysis case, it is assumed that radiation comes directly from the waste, so there is no difference in results between rock types for core exposure and only a slight difference in dose from spoil, (due to a difference in rock density). In view of the timing of the human intrusion scenario, going from the period considered for effective institutional control (300 to 1 ky after closure) to that defined by physical resistance of the waste package (3.5 and 18 ky for HLW and TRU waste package B respectively), decreases the calculated dose by one to two orders of magnitude due to radioactive decay of the inventory.

[14] Plutonic rocks and Pre-Neogene sediments: 0.05, Neogene sediments: 0.06.

Table 6.5-1 Maximum values of dose (mSv) for human intrusion scenarios

Analysis case		Host rock	Effective institutional management time (y)		Physical resistance time (y)	
			300	1,000	18,000 (TRU)	35,000 (HLW)
Worker Exposure case Target dose: 20 to 100 mSv	Spoil analysis	Plutonic	50 (HLW)	20 (HLW/TRU)	6	0.6
		Neogene	60 (HLW)	20 (HLW/TRU)	6	0.7
		Pre-Neogene	50 (HLW)	20 (HLW/TRU)	6	0.6
	Core analysis	Plutonic	40 (HLW/TRU)	20 (TRU)	6	0.4
		Neogene	40 (HLW)	20 (TRU)	4	0.4
		Pre-Neogene	40 (HLW/TRU)	20 (TRU)	6	0.4
Borehole pathway case Target dose: 1 to 20 mSv/y		Plutonic	3 (TRU Gr.2)	0.7 (TRU Gr.1)	0.7 (TRU Gr.1)	4×10^{-5}
		Neogene	7 (TRU Gr.2)	2 (TRU Gr.1)	2 (TRU Gr.1)	9×10^{-5}
		Pre-Neogene	2 (TRU Gr.2)	0.6 (TRU Gr.1)	0.6 (TRU Gr.1)	4×10^{-5}

Notation used
() type of waste that contributes to the maximum dose
HLW: High level radioactive waste
TRU: TRU waste
Gr.: Group

The maximum value of the exposure dose to the general public from the borehole pathway case is due to TRU waste when the scenario occurs 300 y after closure: for plutonic rocks, 3 mSv/y (77 y after drilling); for Neogene sediments, 7 mSv/y (36 y after drilling); and for Pre-Neogene sediments 2 mSv/y (84 y after drilling). In any case, these fall within the target range of 1 to 20 mSv. The largest value is for Neogene sediments, due primarily to shallower repository depth and hence a shorter migration distance. For the 300-y occurrence, Cs-137 (half-life: 30 y) from TRU waste Gr.2 dominates releases from the borehole pathway but, due to decay, this is replaced at 1 ky by I-129 of Gr.1 (half-life: 1.6×10^{7} y). The half-life of I-129 is so long that it is not attenuated even if the duration of physical resistance for TRU waste is considered.

As mentioned in Section 6.5.1 (3) (ii), the probability that the drilling for hot spring development penetrates HLW or TRU waste is thought to be low, the probability of occurrence to calculate risk using the same method as the low probability perturbation scenarios discussed in Section 6.4.3 is investigated.

The frequency of drilling for hot spring development [105] within the range of 300 to 1,000 m depth in Japan was noted to be 1×10^{-9} to $6 \times 10^{-10}/m^2/y$, regardless of terrain. Conservatively assuming $8 \times 10^{-9}/m^2/y$ as the upper limit of this range. As described above, considering both the worker exposure case and borehole pathway cases, the maximum doses result from institutional control for 300 y for Neogene sediments: 60 mSv and 7 mSv/y, respectively. These values can be put into context by considering the area occupied by 40,000 HLW packages (about 6×10^3 m^2) for H12V disposal. Thus, using the dose to risk conversion factor of 5.7×10^{-2}/Sv (see Section 6.1.5 (2)), the integrated risk for the worker exposure case is ≈ 2×10^{-7}/y and for the borehole pathway case ≈ 2×10^{-8}/y, are far below the internationally recommended risk limit of 10^{-5}/y (see Supporting Report 6-34 for details).

Thus, even if only considering a minimum period of institutional control as limiting the earliest time that human intrusion occurs, this conservative analysis indicates that doses would not be unacceptably high and, when coupled to an assessment of likelihood of occurrence, risks are extremely small. Considering the physical resistance of waste packages, the doses further decrease, suggesting that the reference repository design has some robustness to limit impacts of human intrusion scenarios.

6.6 Summary and Future Perspective

6.6.1 Summary of safety evaluations

In this chapter, the three representative SDMs developed in Chapter 3 were assessed, based on repositories tailored to them as described in Chapter 4. In Japan, safety regulations for geological disposal will be defined only in the future, so the framework for conducting safety assessment is not clear at this time, including radiation protection standards, required scenarios for post-closure evaluation and the time scales to be considered. Therefore, for this report, the fundamental concept of safety assessment and the associated regulatory requirements are based on those recommended by international organisations or used in other countries, as was the case for the H12 and TRU-2 studies.

In the safety assessment, a risk-informed approach to assessing radiological impacts is adopted, based on the dose calculated for specific scenarios and the probability of such scenarios occurring. For this disaggregated dose/probability approach, results are compared to targets defined for different categories of scenario (base, variant, low probability perturbation, and human intrusion scenarios). In addition, the basic approach to safety assessment was discussed, along with the assessment period, the RNs to be evaluated and the analytical models and datasets used to calculate doses.

To initiate this approach, systematic methods for developing scenarios belonging to each category were used. After formally describing the behaviour of the repository after closure, facilitated by the use of storyboards, a top-down method of considering the safety functions expected for the components of the repository system was combined with a bottom-up approach based on assessment of relevant FEPs. Such FEPs are compiled from the latest internationally developed databases and the FEP lists used in previous Japanese safety assessment to ensure that the resulting list (NUMO FEP list) is comprehensive.

In developing the models and setting up the data sets for scenario consequence analysis, consideration was given to realistically reflect the characteristics of both the SDM and repository to the extent possible. Specifically, a 3D model is utilised to explicitly evaluate the arrangement of components of the repository with respect to the network of features in which groundwater flows and RNs migrate through a limited portion of the surrounding host rock.

However, it is admitted that the current approach is simplistic and does not fully take into account the 3D aspects of the entire repository and its setting within the SDM.

The model databases include characteristics of repository components derived from the SDMs and assessment of the evolution of the EBS structures situated within them (e.g. hydraulic conductivities reflecting the occurrence of cracks in the structural framework of TRU waste vaults). Here, again, there are many simplifications which constrain the extent to which all characteristics of the repository systems specified can be captured. Databases including, or used to derive, RN migration parameters, such as thermodynamic databases used for setting chemical speciation and elemental solubility in evolving EBS porewater, sorption distribution coefficients and diffusion coefficients are specified, even if all uncertainties associated with their application are not fully assessed.

The analyses of the base scenario indicate that the proposed dose targets can be met for all host rocks/repository design options. The variant scenarios assess impacts of uncertainties in the models and databases used for the base scenario, but most of these have little impact on doses, and all meet the specified dose targets.

The results of dose assessment for low probability perturbation scenarios and human intrusion scenarios also fall within the range of target doses set according to international guidelines. When the assessed probability of occurrence for such scenarios is included, the total risk calculated was also shown to be much lower than the risk constraint values suggested by international organisations.

In conclusion, the assessment indicates that NUMO is well situated to assess the post-closure safety of repositories tailored to the sites likely to result from the volunteering process. Furthermore, no fundamental issues were identified that would call previous assessments of the fundamental feasibility of safe geological disposal in Japan into question. However, further development of the safety assessment methodology, enhancing realism and avoiding over-conservative assumptions, would be needed in later stages of the repository programme.

6.6.2 Extension of assessment to coastal sites

By considering constraints on site acceptability, such as it being favourable for transportation of waste and the high probability of confirmation of favourable characteristics, scientifically preferable areas have been identified [92]. These particularly include coastal areas and small islands.

A study group on “Technical issues for geological disposal under the coastal seafloor” clarified the present state-of-the-art and identified R&D to develop the technology necessary for the repository to be located below the sea, but accessed from land. This included safety considerations of coastal sub-seabed repositories, applicable safety evaluation methodology, examples of safety assessments, and future technical issues to be clarified [111].

In coastal areas, seawater often penetrates under fresh water due to its higher density, forming a saltwater intrusion wedge (see Section 3.1.3 (1)). The freshwater/saltwater interface moves in response to shifts of coastline position due to sea level changes accompanying long-term glacial cycles (although it can also be impacted by human activities, such as water extraction from aquifers). As a result, the direction, flow velocity and chemical properties of groundwater may periodically change, depending on the location of the repository and local topography/bathymetry. Depending on whether the initial location of the repository is in a saltwater or freshwater environment, required EBS material properties and the evolution of the repository system will be different, as will parameters related to RN release and transport (solubility, sorption, diffusion behaviour, etc.). This becomes more complicated if the repository environment cyclically changes between fresh and marine conditions. Also, unlike a repository located far from the coast, in order to calculate radiation doses caused by RNs released from a repository located under the coastal seafloor, it is necessary to consider RN migration processes to a relevant GBI coupled to an associated oceanic biosphere model.

Although not included in this safety case, a safety assessment method for coastal areas has been developed and performed a preliminary evaluation of coastal submarine disposal [112]. For this, key characteristics of relevant geological environments are firstly defined, including uplift/erosion, climate cycles and associated sea level changes. These allow development of evolution scenarios, which can be assessed using models developed to analyse groundwater flow driven by density, variations in salt concentration in groundwater as a result of flow and mixing, etc. These form the basis for conducting RN migration analysis to an identified GBI, using appropriately modified RN release and transport parameters.

In this evaluation, RN migration analysis is carried out for the THMC characteristics expected around the repository, assessed in terms of impacts due to sea level change combined with uplift/erosion. For repositories located under the coastal seabed, the hydraulic gradient is usually extremely small, so very favourable conditions for ensuring safety may be expected. However, this analysis needs to be extended in the future to ensure that it will be mature enough to apply to volunteer sites.

6.6.3 Potential to improve future assessments

In order to further improve the technical basis for safety evaluation, NUMO cooperates with both national and international R&D organisations on the following initiatives.

- In the future, a goal is to make assessments more realistic and to account for all components of the repository system in their specific geological settings. In particular, more realistic RN release and migration models for both the EBS and geosphere should better reflect their 3D characteristics for specific sites and the repository concepts tailored to them, in line with the stepwise improvement of the knowledge base. In addition, more emphasis on model testing, verification and validation will be needed in later stages of this process.
- In order to improve traceability, the methodology involved in the work flow from development of scenarios to setting of analysis cases based on the understanding of the behaviour the repository system will be developed in a more systematic way, utilising advanced knowledge management tools.
- In terms of such technology development, focus will be on the actual volunteer sites in order to ensure that more realistic assessment of safety functions of repositories tailored to them can effectively contribute to the comparison between sites and the optimisation of repository designs for these.
- Continual expansion of the RN release and migration database for relevant geological environments and associated evolution of the EBS for the wastes considered.

Table 6.6-1 shows key issues and technical development items related to these topics.

Table 6.6-1 Technical development tasks to improve post-closure safety assessment

Classification of tasks	Major technical development items
1. Upgrading disposal system models	• Ensure a less simplified description of the 3D characteristics of both the EBS and the geological environment • Improvement of RN release models for all waste types • Improvement of models of evolution/interaction of near field components • Further development and assessment of models of gases derived from waste • Development of evaluation methods for colloids, organics and microorganisms • Testing of model of nitrate impacts • Development of models for, and analyses of, repository component evolution and its impact on safety function, considering couplings between different processes in an integrated fashion • Structured approach to model testing, verification and validation
2. Improvement of scenario development for risk-informed assessment	• Management tool to support RN migration analysis case setting within the scenario development process • Improved sophistication of storyboards • Further studies of human intrusion and low probability perturbation scenarios
3. Advanced modelling of RN migration to capture system evolution	• Modelling of the near field • Modelling of the far field • Improved biosphere modelling to reflect evolution of specific sites
4. Advanced modelling of RN migration to capture facility design	• Construction of advanced RN migration models capturing key aspects of facility design
5. RN-specific database development	• Expansion of the database supporting setting of RN-specific parameters for conditions relevant to repositories • Expansion of data to support evaluations of relevant biospheres • Development of a methodology for defining RN release and migration parameters during stepwise site characterisation

(1) Improving models of the repository

(i) Improvement of RN release models for all waste types

For vitrified HLW, processes that influence glass dissolution rate have already been identified. In the future, long-term immersion tests will be conducted to better quantify the effects of overpack derived iron and protection by alteration layers, aimed to confirm the validity of existing RN release models. Also, based on the knowledge acquired through such testing, improvement of the associated RN dissolution model within the limited volume inside a failed overpack may be considered.

For Gr.2 TRU waste, RN dissolution tests on actual waste, including compacted hulls and end pieces will be conducted, to support development of a more realistic RN release model.

(ii) Improvement of models of evolution/interaction of near field components

To evaluate evolution of near field consisting of several different constituent materials, test data on alteration of buffer by both overpack and cementitious material has been acquired and supporting analytical models have been constructed. In the future, a wider emphasis on the evolving groundwater environment will be developed, explicitly including issues for coastal areas. This will obtain data on thermal, hydraulic, mechanical and chemical aspects of overpack and buffer alteration, in particular, to validate the current models. More generally, when important evolution processes are clarified, the goal will be to capture these in quantitative models. For example, studies on use of cementitious grout during construction of the repository are conducted and a reactive transport model developed to assess the impacts of a resultant alkaline plume on the host rock.

Perturbations related to buffer erosion in the transient period after closure of the repository have also been identified as a concern; thus, acquisition of relevant data for Japanese boundary conditions and development of an analytical model will be carried out, along with associated validity assessment.

(iii) Study of models of waste package derived gases

Gas migration tests of buffer and cementitious materials have been carried out to evaluate the influence of gases generated within a repository on key safety functions. In addition to acquiring relevant data, construction of a model capable of coupled two-phase analysis is being developed. In the future, the validity of this model will be tested by small scale gas migration experiments. After confirming its validity, it will be used to examine the effect of gas on release and transport of RNs.

(iv) Development of models for colloids, organics and microorganisms

To date, the development of a model to quantify the impact of bentonite colloids on RN migration is ongoing. In the future, the production and stability of bentonite colloids will be captured in this model, the validity of which will be tested in various geological environments. With regard to natural colloids present in groundwater, construction of impact assessment models for RN migration are under development for relatively large colloids ($> 0.2\ \mu m$), and it is expected that, in the future, the model will be extended to smaller colloids.

In terms of the effect of organic solutes on release and migration of RNs, assessment has been limited to the influence of isosaccharinic acid (ISA) derived from TRU waste on the solubility of actinide elements, based on a chemical thermodynamic complexation model. To extend this, data on impacts of ISA on the solubility and sorption of transition elements will be obtained, and RN partitioning data in the ternary system of natural organic matter-RN-rock will be obtained and analysed in order to develop a model of its impacts on repository performance.

To assess the effects of microbial activity on RN migration, relevant data on uptake of RNs have been acquired for some specific microorganisms. In the future, this work will be expanded to develop a better overview of the potential issues involved.

(v) Testing of nitrate impact models

Existing approaches for evaluating the influence of nitrate contained in TRU waste Gr.3 on the safety functions of the repository will be extended to better capture direct interactions between nitrate and RNs and thus impacts on RN release and transport. Models will be tested using data acquired by long-term immersion tests and analogue cases of nitrate contamination of groundwater. In addition to direct complexation by nitrate ions, consideration of its potential role as an oxidant will be extended and the impacts of reduction products, such as ammonia, on the mobility of RNs will be assessed.

(vi) Construction of a 4D evolution model

In order to understand temporal and spatial evolution of the repository system, development of a platform that enables analysis by integrating various component alteration models, with a focus on the near field, has been developed. In the future, this will be extended, with the goal of expanding the platform to enable more advanced coupled analysis of all relevant processes. This will aid identification of important issues to further improve the realism of the safety assessment.

(2) Improvement of risk-informed scenario development

(i) Management tool concept

As shown in this report, a methodology for developing scenarios based on their probability has been developed, focused on the evolution of the safety functions of specific repository components. It is planned that management tools will be implemented to ensure traceability of this process, systematically capturing all tacit assumptions and supporting arguments.

In addition, the FEP list required for the scenario development has been updated, through participation in the OECD/NEA FEP Database Project and associated work documented in technical reports. Supporting information will continue to be gathered within national and international R&D projects, updating the FEP list if and when appropriate.

(ii) Improving storyboards

In order to contribute to the completeness of scenarios, storyboards are being developed to capture the latest scientific knowledge from experts in relevant fields and set this in the context of a Japanese repository. In the future, in order to contribute to a consistent representation of the evolution of the repository, including the period before closure, the methodology for construction of storyboards that can capture, synthesise and illustrate a wider range of knowledge will be improved. For example, utilisation of animation can better represent the long-term evolution of repository system and its component parts. When this includes a link function to supporting databases, the general overview can be combined with more detailed, technical information. In order to contribute to development of scenarios compatible to a risk-informed approach, the aim is to incorporate functionality that can visually express different possible evolutions and their associated probabilities.

(iii) Further study of human intrusion and low probability perturbation scenarios

A wider range of credible human intrusion and low probability perturbation scenarios will be developed, with reference to work by relevant Japanese and other national/international organisations. In addition, supporting information (such as assessments of the effectiveness of preservation of records to reduce risks of human intrusion) will continue to be collected with the aim of being able to tailor such scenarios to the boundary conditions of actual sites.

(3) Advanced RN migration models that capture system evolution

(i) Modelling of the near field

For the near field, where processes such as reaction of concrete and buffer are coupled and proceed in a microporous charged environment where normal thermodynamic models are limited or completely inapplicable, acquisition of basic data to support model development will continue. Thus, for example, further data relating to the sorption and diffusion of RNs will be measured in buffer converted to Fe-type, due to corrosion of the overpack, or Ca-type, by cementitious leachate from material. In the future, a more realistic near field evolution model will be developed, based on data on the behaviour of RNs in cementitious buffer materials as alteration progresses. Advanced R&D aims both to establish RN migration models applicable to such an evolving system and test their validity to the extent possible.

(ii) Modelling of the far field

To advance models of the migration of RNs within fractured rock, it is intended to go beyond the simple treatment of regular channels in parallel plate fractures to allow more realistic representation of the micro-scale models of water conducting fractures in crystalline rock (e.g. granite) and also other relevant features in sedimentary rock (e.g. sand channels in mudstone). Such improved representation of the RN migration paths will be complemented by expanded databases of interactions that result in retardation, including diffusion into, and sorption onto, relevant phases resulting from rock-water interaction as described in the SDMs. Model development will proceed in parallel to establishing test cases to validate both hydrological and solute transport models over larger scales (extending from several tens to a hundred metres or so, and times of many years).

(iii) Improved biosphere modelling to reflect geological evolution

Based on evaluation of Japan as a whole from the viewpoint of climate and topography, a simple generic biosphere compartment model has been developed that allows assessment of doses to specified critical groups for certain stylised RN release scenarios. In the future, in order to express capture of the surface environment more realistically, this model will be refined by improving the compartment representations in order to reflect changes with time and the spatial extent of the GBI, based on a long-term evolution model of the geological environment. It is intended that this will focus on actual volunteer sites as soon as they are available, also taking local lifestyle into account, especially for coastal communities.

(4) Advanced RN migration models that capture repository design

In the future, in addition to improving the computational capability to support more extensive and detailed 3D solute transport modelling, it is necessary to demonstrate model consistency between the spatial scales considered (regional to repository scale, panel scale and near field scale) to allow differences between different repository layouts and EBS designs to be assessed. This will require models that can realistically quantify RN migration for the geometry, layout and physicochemical characteristics of the constituent components of the repository, but also capture their temporal evolution, e.g. as a result of changes of the groundwater flow field and groundwater chemistry due to climate/sea level change. In order to perform such analysis more efficiently, high-speed processing methods will be utilised, such as parallel computation.

(5) RN-specific database development

(i) Expansion of data required for RN release and transport models

The thermodynamic database (TDB), sorption database (SDB) and diffusion database (DDB) utilised for performance assessment are continuously expanded through laboratory research and review of the technical literature. In the future, particular emphasis will be placed on accumulating relevant data for rocks and geochemical conditions relevant to the coastal submarine environment.

In particular, as shown in this report, the measurement database under high carbonate concentrations is poor and hence RN migration parameters were set in an extremely conservative manner and thus yield unrealistically high doses (even if these are below specified targets). For this reason, data acquisition to determine more realistic RN migration parameters for high carbonate groundwater under reducing environments is a future focus. Acquisition of data in such systems is experimentally difficult and, to interpret such data, development of a mechanistic sorption model more suited to such an environment will also be considered.

In addition, associated with model development noted in (1) and (3) above, databases for setting RN release and migration parameters taking into consideration long-term system evolution due to interaction between the EBS components and the surrounding geosphere will be developed (e.g., sorption data of RNs under high-concentrations of nitrate, sorption data of RNs on Ca-type bentonite, etc.).

(ii) Expansion of biosphere data

Acquisition of data such as sorption distribution coefficients of relevant RNs onto surface soil and research on carbon cycling mechanisms in the biosphere have so far been carried out for Japan as a whole. In the future, there will be a focus on areas relevant to specific sites, including the coastal ocean floor, where data necessary for biosphere assessment is not sufficiently developed. In addition, data determining the behaviour of iodine and actinides (together with their daughters), which were identified as particularly relevant in this report, will be a focus.

(iii) Refinement of RN migration parameters following site surveys

So far, data acquired in the laboratory under test conditions was applied, focusing on generic geological environments in order to set parameters such as sorption distribution coefficients and diffusion coefficients. From now on, based on geological information acquired during investigations of actual sites, focused data on such parameters will be obtained, as preparation for preliminary investigation area (PIA) and detailed investigation area (DIA) selection.

Supporting Reports (SRs)

SR 6-1 Biosphere assessment models and parameters
SR 6-2 Time period for safety assessment
SR 6-3 International approach to scenario section and setting performance goals
SR 6-4 NUMO FEP list
SR 6-5 FEP screening and integration
SR 6-6 Safety function diagrams used for scenario construction
SR 6-7 Factor analysis diagrams
SR 6-8 Process analysis used for impact assessment
SR 6-9 Impact analysis tables for safety functions
SR 6-10 Examination of the effects of uplift / erosion
SR 6-11 Storyboards
SR 6-12 Summary and verification of analysis codes used for post-closure safety evaluation
SR 6-13 Radionuclide release and migration models
SR 6-14 Near-field 3D groundwater flow and particle tracking models
SR 6-15 Setting porewater chemistry in the EBS
SR 6-16 Permeability of cementitious materials
SR 6-17 Setting solubilities in EBS porewater
SR 6-18 Setting speciation in groundwater and buffer porewater
SR 6-19 Setting diffusion coefficients in the EBS
SR 6-20 Setting EBS sorption distribution coefficients
SR 6-21 Setting diffusion coefficients in host rock
SR 6-22 Setting sorption distribution coefficients in the host rock
SR 6-23 Representation of fault zones in the safety assessment (based on H12)
SR 6-24 Results of the safety assessment for plutonic rocks (base and variant cases)
SR 6-25 Results of the safety assessment for Neogene sedimentary rocks (base and variant cases)
SR 6-26 Results of the safety assessment for Pre-Neogene sedimentary rocks (base and variant cases)
SR 6-27 New volcano scenarios
SR 6-28 Fault extension scenarios
SR 6-29 Requirements for development of human intrusion scenarios
SR 6-30 Human intrusion scenarios
SR 6-31 Human intrusion scenario constraints
SR 6-32 Human intrusion scenario migration paths
SR 6-33 Analysis models and data for human intrusion scenarios
SR 6-34 Safety assessment results for human intrusion scenarios
SR 6-35 Study of the effects of high carbonate groundwater

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Appendix

Table 1 NUMO FEP List

No.	FEP No.	FEP name
1	F1.1.1	Quality assurance and control
2	F1.1.2	Site investigations
3	F1.1.3	Repository design
4	F1.1.4	Schedule and planning
5	F1.1.5	Construction
6	F1.1.6	Operation
7	F1.1.7	Closure
8	F1.1.8	Accidents and unplanned events
9	F1.1.9	Repository administrative control
10	F1.1.10	Monitoring
11	F1.1.11	Repository markers
12	F1.2.1	Tectonic movement
13	F1.2.2	Orogeny
14	F1.2.3	Deformation (elastic, plastic, or brittle)
15	F1.2.4	Seismicity
16	F1.2.5	Volcanic and magmatic activity
17	F1.2.6	Metamorphism
18	F1.2.7	Hydrothermal activity
19	F1.2.8	Regional erosion and sedimentation
20	F1.2.9	Diagenesis
21	F1.2.10	Pedogenesis
22	F1.2.12	Hydrological/Hydrogeological response to geological changes
23	F1.2.13	Geomorphological response to geological changes
24	F1.3.1	Global climate change
25	F1.3.2	Regional and local climate change
26	F1.3.3	Sea level change
27	F1.3.4	Periglacial effects
28	F1.3.5	Local glacial and ice-sheet effects
29	F1.3.6	Warm climate effects (tropical and desert)

No.	FEP No.	FEP name
30	F1.3.7	Hydrological response to climate change
31	F1.3.8	Ecological response to climate change
32	F1.3.9	Human response to climate change
33	F1.3.10	Geomorphological response to climate changes
34	F1.4.1	Human influences on climate
35	F1.4.2	Social and institutional developments
36	F1.4.3	Technological developments
37	F1.4.4	Knowledge and motivational issues (repository)
38	F1.4.5	Drilling activities
39	F1.4.6	Mining and other underground activities
40	F1.4.7	Unintrusive site investigation
41	F1.4.8	Surface Environment
42	F1.4.9	Water management (groundwater and surface water)
43	F1.4.10	Explosions and crashes
44	F1.4.11	Remedial Actions
45	F1.4.12	Deliberate human intrusion
46	F1.5.1	Meteorites and human space debris
47	F1.5.2	Evolution of biota
48	F2.1.1.1	Solid
49	F2.1.2.1	Metallic wastes
50	F2.1.2.2	Organic wastes
51	F2.1.2.3	Non-metallic, inorganic wastes
52	F2.1.3	Waste conditioning matrix
53	F2.1.4.1	Radionuclide content
54	F2.1.4.2	Chemical content
55	F2.1.5	Waste form properties
56	F2.2.1	Containers

No.	FEP No.	FEP name
57	F2.2.2	Overpacks
58	F2.3.1.1	Radiogenic heat production and transfer
59	F2.3.1.2	Chemical heat production and transfer
60	F2.3.1.3	Biological heat production and transfer
61	F2.3.1.4	Impact of thermal processes on other processes (waste package)
62	F2.3.2.1	Resaturation/desaturation (waste package)
63	F2.3.2.2	Thermal effects (waste package)
64	F2.3.2.3	Gas effects (waste package)
65	F2.3.2.4	Impact of hydraulic processes on other processes (waste package)
66	F2.3.3.1	Package deformation
67	F2.3.3.2	Material volume changes (waste package)
68	F2.3.3.3	Package movement
69	F2.3.3.4	Stress corrosion cracking
70	F2.3.3.5	Gas explosion (waste package)
71	F2.3.3.6	Impact of mechanical processes on other processes (waste package)
72	F2.3.4.1	pH conditions (waste package)
73	F2.3.4.2	Redox conditions (waste package)
74	F2.3.4.3	Perturbing species' concentrations (waste package)
75	F2.3.4.4	Corrosion (waste package)
76	F2.3.4.5	Polymer degradation (waste package)
77	F2.3.4.6	Dissolution (waste package)
78	F2.3.4.7	Mineralisation (waste package)
79	F2.3.4.8	Precipitation reactions (waste package)
80	F2.3.4.9	Chelating agent effects (waste package)
81	F2.3.4.10	Colloid formation (waste package)
82	F2.3.4.11	Chemical concentration gradients (waste package)
83	F2.3.4.12	Impact of chemical processes on other processes (waste package)

No.	FEP No.	FEP name
84	F2.3.5.1	Microbial growth and poisoning (waste package)
85	F2.3.5.2	Microbially/biologically mediated processes (waste package)
86	F2.3.5.3	Impact of biological processes on other processes (waste package)
87	F2.3.6.1	Radioactive decay and ingrowth (waste package)
88	F2.3.6.2	Radiolysis (waste package)
89	F2.3.6.3	Helium production
90	F2.3.6.4	Radiation attenuation (waste package)
91	F2.3.6.5	Radiation damage (waste package)
92	F2.3.6.6	Impact of radiological processes on other processes (waste package)
93	F2.3.7.1	Metal corrosion (waste package)
94	F2.3.7.2	Organic degradation (waste package)
95	F2.3.7.3	Radon production (waste package)
96	F2.3.7.4	Radiolysis (waste package)
97	F2.3.7.5	Volatilisation (waste package)
98	F2.3.7.6	Gas dissolution (waste package)
99	F2.3.7.7	Gas-induced failure
100	F2.3.7.8	Impact of gas generation on other processes (waste package)
101	F2.4.1.2	Dissolution (waste form)
102	F2.4.1.3	Diffusion (waste form)
103	F2.4.1.4	Speciation and solubility (waste form)
104	F2.4.1.5	Sorption and desorption (waste form)
105	F2.4.1.6	Complexation (waste form)
106	F2.4.1.7	Colloids
107	F2.4.2.1	Gaseous wastes
108	F2.4.2.2	Radon production (waste form)
109	F2.4.2.3	Volatilisation (waste form)
110	F2.4.2.4	Radiolysis (waste form)
111	F2.4.3	Solid-mediated release
112	F2.4.4	Human-action-mediated release

No.	FEP No.	FEP name
113	F2.5.1	Transport pathways (waste package)
114	F2.5.2.1	Advection (waste package)
115	F2.5.2.2	Dispersion (waste package)
116	F2.5.2.3	Molecular diffusion (waste package)
117	F2.5.2.4	Dissolution, precipitation, and mineralisation (waste package)
118	F2.5.2.5	Speciation and solubility (waste package)
119	F2.5.2.6	Sorption and desorption (waste package)
120	F2.5.2.7	Complexation (waste package)
121	F2.5.2.8	Colloid transport (waste package)
122	F2.5.3	Gas-mediated transport (waste package)
123	F3.1.1	Design
124	F3.1.2	Buffer/backfill
125	F3.1.3	Room/tunnel seals
126	F3.1.4	Shaft/ramp seals
127	F3.1.5	Other engineered features
128	F3.1.6	Excavation damaged and disturbed zones
129	F3.2.1.1	Thermal conduction and convection
130	F3.2.1.2	Impact of thermal processes on other processes (repository)
131	F3.2.2.1	Resaturation/desaturation (repository)
132	F3.2.2.2	Piping/hydraulic erosion
133	F3.2.2.3	Impact of hydraulic processes on other processes (repository)
134	F3.2.3.1	Material volume changes (repository)
135	F3.2.3.2	Creep
136	F3.2.3.4	Gas explosion (repository)
137	F3.2.3.5	Impact of mechanical process on other processes (repository)
138	F3.2.4.1	pH conditions (repository)
139	F3.2.4.2	Redox conditions (repository)
140	F3.2.4.3	Perturbing species' concentrations (repository)
141	F3.2.4.4	Corrosion (repository)

No.	FEP No.	FEP name
142	F3.2.4.5	Dissolution (repository)
143	F3.2.4.6	Mineralisation (repository)
144	F3.2.4.7	Precipitation reactions (repository)
145	F3.2.4.8	Chelating agent effects (repository)
146	F3.2.4.9	Colloid formation (repository)
147	F3.2.4.10	Chemical concentration gradients (repository)
148	F3.2.4.11	Impact of chemical processes on other processes (repository)
149	F3.2.4.12	Polymer degradation (repository)
150	F3.2.5.1	Microbial growth and poisoning (repository)
151	F3.2.5.2	Microbially/biologically mediated processes (repository)
152	F3.2.5.3	Impact of biological processes on other processes (repository)
153	F3.2.6.1	Radioactive decay and ingrowth (repository)
154	F3.2.6.2	Radiolysis (repository)
155	F3.2.6.3	Radiation attenuation (repository)
156	F3.2.6.4	Radiation damage (repository)
157	F3.2.6.5	Criticality
158	F3.2.6.6	Impact of radiological processes on other processes (repository)
159	F3.2.7.1	Metal corrosion (repository)
160	F3.2.7.2	Organic degradation (repository)
161	F3.2.7.3	Radon production (repository)
162	F3.2.7.4	Radiolysis (repository)
163	F3.2.7.5	Volatilisation (repository)
164	F3.2.7.6	Gas dissolution (repository)
165	F3.2.7.7	Gas-induced dilation (repository)
166	F3.2.7.8	Impact of gas generation on other processes (repository)
167	F3.3.1	Transport pathways (repository)
168	F3.3.2.1	Advection (repository)
169	F3.3.2.2	Dispersion (repository)
170	F3.3.2.3	Molecular diffusion (repository)
171	F3.3.2.4	Dissolution, precipitation, and mineralisation (repository)

No.	FEP No.	FEP name
172	F3.3.2.5	Speciation and solubility (repository)
173	F3.3.2.6	Sorption and desorption (repository)
174	F3.3.2.7	Complexation (repository)
175	F3.3.2.8	Colloid transport (repository)
176	F3.3.3	Gas-mediated transport (repository)
177	F3.3.4	Solid-mediated transport (repository)
178	F3.3.5	Human-action-mediated transport (repository)
179	F4.1.1	Stratigraphy
180	F4.1.2	Host rock lithology
181	F4.1.3	Large-scale discontinuities
182	F4.1.4	Geological resources
183	F4.1.5	Undetected features
184	F4.1.6	Current geothermal state
185	F4.1.7	Current hydraulic state
186	F4.1.8	Current stress state
187	F4.1.9	Current geochemical state
188	F4.1.10	Current biological state
189	F4.1.11	Current gas state
190	F4.2.1.1	Thermal effects of repository (geosphere)
191	F4.2.1.2	Thermal effects of climate change (geosphere)
192	F4.2.1.3	Other processes affecting future thermal conditions in geosphere
193	F4.2.2.1	Hydraulic effects of repository (geosphere)
194	F4.2.2.2	Hydraulic effects of climate change (geosphere)
195	F4.2.2.3	Other processes affecting future hydraulic conditions in the geosphere
196	F4.2.3.1	Mechanical effects of repository (geosphere)
197	F4.2.3.2	Mechanical effects of climate change (geosphere)
198	F4.2.3.3	Other processes affecting future stress conditions in geosphere

No.	FEP No.	FEP name
199	F4.2.4.1	Geochemical effects of repository (geosphere)
200	F4.2.4.2	Geochemical effects of climate change (geosphere)
201	F4.2.4.3	Other processes affecting future geochemical conditions in geosphere
202	F4.2.5.1	Biological effects of repository (geosphere)
203	F4.2.5.2	Biological effects of climate change (geosphere)
204	F4.2.5.3	Other processes affecting future biological conditions in geosphere
205	F4.2.6	Radiological processes (geosphere)
206	F4.2.7.1	Gas sources (geosphere)
207	F4.2.7.2	Radon production (geosphere)
208	F4.2.7.3	Volatilisation (geosphere)
209	F4.2.7.4	Gas dissolution (geosphere)
210	F4.2.7.5	Gas-induced dilation (geosphere)
211	F4.3.1	Transport pathways (geosphere)
212	F4.3.2.1	Advection (geosphere)
213	F4.3.2.2	Dispersion (geosphere)
214	F4.3.2.3	Molecular diffusion (geosphere)
215	F4.3.2.4	Matrix diffusion
216	F4.3.2.5	Dissolution, precipitation, and mineralisation (geosphere)
217	F4.3.2.6	Speciation and solubility (geosphere)
218	F4.3.2.7	Sorption and desorption (geosphere)
219	F4.3.2.8	Complexation (geosphere)
220	F4.3.2.9	Colloid transport (geosphere)
221	F4.3.3	Gas-mediated transport (geosphere)
222	F4.3.4	Solid-mediated transport (geosphere)
223	F4.3.5	Human-action-mediated transport (geosphere)
224	F5.1.1	Topography and morphology
225	F5.1.2	Biomes
226	F5.1.3.1	Surface soils
227	F5.1.3.2	Overburden

No.	FEP No.	FEP name
228	F5.1.3.3	Aquatic sediments
229	F5.1.4	Near-surface aquifers and water-bearing features
230	F5.1.5.1	Wetlands
231	F5.1.5.2	Lakes and rivers
232	F5.1.5.3	Spring and discharge zones
233	F5.1.6	Coastal features
234	F5.1.7	Marine features
235	F5.1.8	Atmosphere
236	F5.1.9	Vegetation
237	F5.1.10	Animals
238	F5.1.11	Climate and weather
239	F5.1.12	Hydrological regime and water balance (near-surface)
240	F5.1.13	Erosion and deposition
241	F5.1.14	Ecological/biological/microbial systems
242	F5.2.1	Human characteristics (physiology, metabolism)
243	F5.2.2	Age, gender, and ethnicity
244	F5.2.3.1	Farming diet
245	F5.2.3.2	Hunter/gatherer diet
246	F5.2.3.3	Other diets
247	F5.2.4	Habits (excluding diet)
248	F5.2.5.1	Community type
249	F5.2.5.2	Community location
250	F5.2.5.3	Water source
251	F5.2.6	Food preparation and water processing
252	F5.2.7	Dwellings
253	F5.2.8	Natural/semi-natural land and water use
254	F5.2.9	Rural/agricultural land and water use
255	F5.2.10	Urban/industrial land and water use
256	F5.2.11	Leisure and other uses of the environment
257	F5.3.1.1	Groundwater discharge to biosphere
258	F5.3.1.2	Transport associated with surface soil and overburden

No.	FEP No.	FEP name
259	F5.3.1.3	Transport associated with surface water bodies
260	F5.3.1.4	Dissolution and precipitation (biosphere)
261	F5.3.1.5	Speciation and solubility (biosphere)
262	F5.3.1.6	Sorption and desorption (biosphere)
263	F5.3.1.7	Complexation (biosphere)
264	F5.3.1.8	Colloid transport (biosphere)
265	F5.3.2.1	Gas discharge to biosphere
266	F5.3.2.2	Radon production (biosphere)
267	F5.3.2.3	Volatilisation from soil/water
268	F5.3.3	Solid-mediated transport (biosphere)
269	F5.3.4	Human-action-mediated transport (biosphere)
270	F5.3.5	Atmospheric transport and deposition
271	F5.3.6	Biologically-mediated transport
272	F5.3.7	Foodchains and uptake of contaminants
273	F5.4.1	Contaminated drinking water and food
274	F5.4.2	Contaminated non-food products
275	F5.4.3	Other contaminated environmental media
276	F5.4.4.1	Exposure of humans
277	F5.4.4.2	Exposure of biota other than humans
278	F5.4.5.1	Dosimetry and biokinetics for humans
279	F5.4.5.2	Dosimetry and biokinetics for biota other than humans
280	F5.4.6.1	Radiological toxicity/effects for humans
281	F5.4.6.2	Radiological toxicity/effects for biota other than humans
282	F5.4.7.1	Chemical toxicity/effects for humans
283	F5.4.7.2	Chemical toxicity/effects for biota other than humans
284	F5.4.8	Radon and radon daughter exposure

Table 2 NUMO FEP list classification scheme (level 1 and level 2)

Level 1[1]	Level 2
F1 EXTERNAL FACTORS	F1.1 Repository issues
	F1.2 Geological factors
	F1.3 Climatic factors
	F1.4 Future human actions
	F1.5 Other external factors
F2 WASTE PACKAGE FACTORS	F2.1 Waste form characteristics and properties
	F2.2 Waste packaging characteristics and properties
	F2.3 Waste package processes[2]
	F2.4 Contaminant release (from waste form)
	F2.5 Contaminant transport (waste package)
F3 REPOSITORY FACTORS	F3.1 Repository characteristics and properties
	F3.2 Repository processes[2]
	F3.3 Contaminant transport (repository)
F4 GEOSPHERE FACTORS	F4.1 Geosphere characteristics and properties
	F4.2 Geosphere processes[2]
	F4.3 Contaminant transport (geosphere)
F5 BIOSPHERE FACTORS	F5.1 Surface environment
	F5.2 Human behaviour
	F5.3 Contaminant transport (biosphere)
	F5.4 Exposure factors

[1] The NUMO FEP consists of a maximum of four hierarchical levels as indicated in the FEP number. Table 6-2 shows the classification of levels 1 and 2. F1 External factors, F2.2 Characteristics and properties of packaged waste, F3.1 Characteristics and properties of the repository, and F4.1 Characteristics and properties of the host rock are up to level 3, and the others are up to level 4.

[2] F2.3, F3.2 and F4.2 have a common structure. Level 3 is divided into thermal processes, hydraulic processes, mechanical processes, chemical processes, biological processes, radiological processes, and processes related to gases, which are listed as FEPs representing specific phenomena in level 4.

Table 3 Integrated FEP list

FEP No.	FEP name
IF1	Orogeny
IF2	Deformation of geosphere
IF3	Seismicity
IF4	Volcanic and magmatic activity
IF5	Hydrothermal activity
IF6	Regional erosion and sedimentation
IF7	Diagenesis
IF8	Climate change
IF9	Radiolysis
IF10	Radiation damage
IF11	Thermal processes
IF12	Resaturation/desaturation
IF13	Package deformation
IF14	Package movement
IF15	Water chemistry
IF16	Corrosion
IF17	Polymer degradation
IF18	Dissolution
IF19	Precipitation reactions
IF20	Chemical alteration
IF21	Microbially/biologically mediated processes
IF22	Gas phase formation
IF23	Water transport
IF24	Piping/hydraulic erosion
IF25	Material volume changes
IF26	Creep
IF27	Undetected geosphere features
IF28	Hydraulic effects of repository
IF29	Mechanical effects of repository

Table 4　Excavation damaged zone (EDZ) flow rate (m^3/y)

			Rock type		
			Plutonic	Neogene	Pre-Neogene
Repository	HLW (H12V)		8×10^{-1}	7×10^{-2}	6×10^{-2}
	HLW (PEM)		8×10^{-1}	7×10^{-2}	6×10^{-2}
	TRU Gr.1		4×10	4	3
	TRU Gr.2		8×10^{2}	1×10^{2}	6×10
	TRU Gr.3		4×10^{2}	5×10	3×10
	TRU Gr.4H	Gr.4HD	9×10^{2}	1×10	7
		Gr.4HH	2×10^{2}	2×10	1×10
	TRU Gr.4L	Gr.4LC	4×10	3	3
		Gr.4LD	4×10^{2}	4×10	3×10

* Gr.4HD: Group 4H (Drum), Gr.4HH: Group 4H (MHHRW), Gr.4LD: Group 4L (Drum), Gr.4LC: Group 4H (Box container)

In Tables 6-5 to 6-23, high level radioactive waste is abbreviated as HLW, TRU waste is abbreviated as TRU, and groups of TRU are abbreviated as Gr.

Table 5 Buffer porewater chemistry

Rock type	Plutonic		Neogene sediments		Pre-Neogene sediments	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
pH	7.2~9.6	7.1~8.4	7.2 ~9.8	6.3~6.5	7.1~9.6	6.1~6.3
Eh (mV)	$-4.1\times10^{2} \sim -2.0\times10^{2}$	$-3.2\times10^{2} \sim -2.0\times10^{2}$	$-3.9\times10^{2} \sim -1.9\times10^{2}$	$-1.7\times10^{2} \sim -1.4\times10^{2}$	$-4.0\times10^{2} \sim -2.0\times10^{2}$	$-1.7\times10^{2} \sim -1.4\times10^{2}$
Ionic strength	$4.2\times10^{-3} \sim 2.1\times10^{-1}$	$5.1\times10^{-2} \sim 2.5\times10^{-1}$	$3.6\times10^{-3} \sim 2.1\times10^{-1}$	$2.4\times10^{-1} \sim 4.0\times10^{-1}$	$3.6\times10^{-3} \sim 2.0\times10^{-1}$	$2.4\times10^{-1} \sim 4.0\times10^{-1}$
Na (total)	$3.1\times10^{-3} \sim 1.6\times10^{-1}$	$1.7\times10^{-2} \sim 2.0\times10^{-1}$	$2.8\times10^{-3} \sim 1.6\times10^{-1}$	$2.2\times10^{-1} \sim 3.4\times10^{-1}$	$2.8\times10^{-3} \sim 1.6\times10^{-1}$	$2.2\times10^{-1} \sim 3.4\times10^{-1}$
Ca (total)	$1.5\times10^{-5} \sim 4.3\times10^{-3}$	$4.7\times10^{-4} \sim 1.6\times10^{-2}$	$1.4\times10^{-5} \sim 4.2\times10^{-3}$	$3.5\times10^{-3} \sim 1.5\times10^{-2}$	$1.4\times10^{-5} \sim 4.3\times10^{-3}$	$3.5\times10^{-3} \sim 1.5\times10^{-2}$
K (total)	$1.6\times10^{-5} \sim 8.3\times10^{-4}$	$1.0\times10^{-4} \sim 1.0\times10^{-3}$	$3.0\times10^{-5} \sim 8.3\times10^{-4}$	$1.9\times10^{-3} \sim 3.2\times10^{-3}$	$3.0\times10^{-5} \sim 8.2\times10^{-4}$	$1.9\times10^{-3} \sim 3.2\times10^{-3}$
Mg (total)	$4.6\times10^{-7} \sim 3.7\times10^{-4}$	$1.7\times10^{-5} \sim 5.3\times10^{-4}$	$4.0\times10^{-7} \sim 3.0\times10^{-4}$	$1.4\times10^{-3} \sim 4.9\times10^{-3}$	$4.1\times10^{-7} \sim 3.6\times10^{-4}$	$1.6\times10^{-3} \sim 4.9\times10^{-3}$
Fe (total)	$7.0\times10^{-7} \sim 1.1\times10^{-6}$	$7.6\times10^{-9} \sim 5.0\times10^{-7}$	$8.4\times10^{-7} \sim 8.6\times10^{-7}$	$1.7\times10^{-11} \sim 3.3\times10^{-5}$	$8.3\times10^{-7} \sim 9.0\times10^{-7}$	$1.7\times10^{-11} \sim 3.3\times10^{-5}$
Al (total)	7.9×10^{-7}	2.8×10^{-7}	2.2×10^{-8}	1.3×10^{-9}	4.3×10^{-8}	2.4×10^{-9}
Si (total)	$4.8\times10^{-4} \sim 1.4\times10^{-3}$	$4.7\times10^{-4} \sim 5.8\times10^{-4}$	$3.3\times10^{-4} \sim 9.4\times10^{-4}$	$3.1\times10^{-4} \sim 3.2\times10^{-4}$	$4.8\times10^{-4} \sim 1.3\times10^{-3}$	$4.4\times10^{-4} \sim 4.6\times10^{-4}$
S (total)	$7.2\times10^{-6} \sim 7.8\times10^{-2}$	$2.0\times10^{-5} \sim 7.8\times10^{-2}$	$1.2\times10^{-4} \sim 7.8\times10^{-2}$	$4.1\times10^{-6} \sim 7.7\times10^{-2}$	$1.2\times10^{-4} \sim 7.8\times10^{-2}$	$4.1\times10^{-6} \sim 7.7\times10^{-2}$
TIC	$9.6\times10^{-4} \sim 7.9\times10^{-3}$	$1.2\times10^{-4} \sim 4.6\times10^{-3}$	$1.6\times10^{-3} \sim 9.1\times10^{-3}$	$3.1\times10^{-2} \sim 4.0\times10^{-2}$	$1.7\times10^{-3} \sim 8.6\times10^{-3}$	$3.6\times10^{-2} \sim 4.7\times10^{-2}$
Cl (total)	$2.3\times10^{-3} \sim 4.5\times10^{-3}$	$4.9\times10^{-2} \sim 5.1\times10^{-2}$	$1.1\times10^{-3} \sim 3.3\times10^{-3}$	2.1×10^{-1}	$1.1\times10^{-3} \sim 3.3\times10^{-3}$	2.1×10^{-1}
F (total)	5.7×10^{-4}	1.3×10^{-4}	1.9×10^{-4}	6.5×10^{-6}	1.9×10^{-4}	6.5×10^{-6}
B (total)	4.6×10^{-6}	2.7×10^{-4}	4.6×10^{-6}	1.0×10^{-2}	4.6×10^{-6}	1.0×10^{-2}
P (total)	6.5×10^{-7}	5.3×10^{-6}	5.6×10^{-6}	5.9×10^{-6}	5.6×10^{-6}	5.9×10^{-6}
N (total)	2.0×10^{-5}	2.8×10^{-5}	2.5×10^{-6}	1.0×10^{-2}	2.5×10^{-6}	1.0×10^{-2}
Br (total)	4.3×10^{-6}	3.9×10^{-5}	4.4×10^{-6}	8.0×10^{-4}	4.4×10^{-6}	8.0×10^{-4}
I (total)	7.9×10^{-6}	5.5×10^{-6}	3.9×10^{-6}	1.8×10^{-4}	3.9×10^{-6}	1.8×10^{-4}

*Solute concentrations and ionic strength in mol/l

Table 6 Porewater chemistry inside HLW overpack

Rock type	Plutonic		Neogene sediments		Pre-Neogene sediments	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
pH	7.2 ~ 9.6	7.1 ~ 8.4	7.2 ~ 9.8	6.4 ~ 6.6	7.1 ~ 9.6	6.2 ~ 6.4
Eh (mV)	$-4.1\times10^{2} \sim -1.5\times10^{2}$	$-3.2\times10^{2} \sim -1.7\times10^{2}$	$-3.9\times10^{2} \sim -8.9\times10$	$-1.7\times10^{2} \sim -1.3\times10^{2}$	$-4.0\times10^{2} \sim -1.3\times10^{2}$	$-1.7\times10^{2} \sim -1.4\times10^{2}$
Ionic strength	$4.2\times10^{-3} \sim 2.1\times10^{-1}$	$5.1\times10^{-2} \sim 2.5\times10^{-1}$	$3.6\times10^{-3} \sim 2.1\times10^{-1}$	$2.4\times10^{-1} \sim 4.0\times10^{-1}$	$3.6\times10^{-3} \sim 2.0\times10^{-1}$	$2.4\times10^{-1} \sim 4.0\times10^{-1}$
Na (total)	$3.1\times10^{-3} \sim 1.6\times10^{-1}$	$1.7\times10^{-2} \sim 2.0\times10^{-1}$	$2.8\times10^{-3} \sim 1.6\times10^{-1}$	$2.2\times10^{-1} \sim 3.4\times10^{-1}$	$2.8\times10^{-3} \sim 1.6\times10^{-1}$	$2.2\times10^{-1} \sim 3.4\times10^{-1}$
Ca (total)	$1.5\times10^{-5} \sim 4.3\times10^{-3}$	$4.7\times10^{-4} \sim 1.6\times10^{-2}$	$1.4\times10^{-5} \sim 4.2\times10^{-3}$	$3.5\times10^{-3} \sim 1.5\times10^{-2}$	$1.4\times10^{-5} \sim 4.3\times10^{-3}$	$3.5\times10^{-3} \sim 1.5\times10^{-2}$
K (total)	$1.6\times10^{-5} \sim 8.3\times10^{-4}$	$1.0\times10^{-4} \sim 1.0\times10^{-3}$	$3.0\times10^{-5} \sim 8.3\times10^{-4}$	$1.9\times10^{-3} \sim 3.2\times10^{-3}$	$3.0\times10^{-5} \sim 8.2\times10^{-4}$	$1.9\times10^{-3} \sim 3.2\times10^{-3}$
Mg (total)	$4.6\times10^{-7} \sim 3.7\times10^{-4}$	$1.7\times10^{-5} \sim 5.3\times10^{-4}$	$4.0\times10^{-7} \sim 3.0\times10^{-4}$	$1.4\times10^{-3} \sim 4.9\times10^{-3}$	$4.1\times10^{-7} \sim 3.6\times10^{-4}$	$1.6\times10^{-3} \sim 4.9\times10^{-3}$
Fe (total)	$2.1\times10^{-9} \sim 1.6\times10^{-6}$	$5.1\times10^{-8} \sim 4.2\times10^{-6}$	$1.3\times10^{-9} \sim 1.2\times10^{-6}$	$5.4\times10^{-4} \sim 8.9\times10^{-4}$	$1.7\times10^{-9} \sim 1.2\times10^{-6}$	$4.1\times10^{-4} \sim 7.5\times10^{-4}$
Al (total)	7.9×10^{-7}	2.8×10^{-7}	2.2×10^{-8}	1.3×10^{-9}	4.3×10^{-8}	2.4×10^{-9}
Si (total)	$4.8\times10^{-4} \sim 1.4\times10^{-3}$	$4.7\times10^{-4} \sim 5.8\times10^{-4}$	$3.3\times10^{-4} \sim 9.4\times10^{-4}$	$3.1\times10^{-4} \sim 3.2\times10^{-4}$	$4.8\times10^{-4} \sim 1.3\times10^{-3}$	$4.4\times10^{-4} \sim 4.6\times10^{-4}$
S (total)	$7.2\times10^{-6} \sim 7.8\times10^{-2}$	$2.0\times10^{-5} \sim 7.8\times10^{-2}$	$1.2\times10^{-4} \sim 7.8\times10^{-2}$	$4.1\times10^{-6} \sim 7.7\times10^{-2}$	$1.2\times10^{-4} \sim 7.8\times10^{-2}$	$4.1\times10^{-6} \sim 7.7\times10^{-2}$
TIC	$9.6\times10^{-4} \sim 7.9\times10^{-3}$	$1.2\times10^{-4} \sim 4.6\times10^{-3}$	$1.6\times10^{-3} \sim 9.1\times10^{-3}$	$3.1\times10^{-2} \sim 4.0\times10^{-2}$	$1.7\times10^{-3} \sim 8.6\times10^{-3}$	$3.6\times10^{-2} \sim 4.7\times10^{-2}$
Cl (total)	$2.3\times10^{-3} \sim 4.5\times10^{-3}$	$4.9\times10^{-2} \sim 5.1\times10^{-2}$	$1.1\times10^{-3} \sim 3.3\times10^{-3}$	2.1×10^{-1}	$1.1\times10^{-3} \sim 3.3\times10^{-3}$	2.1×10^{-1}
F (total)	5.7×10^{-4}	1.3×10^{-4}	1.9×10^{-4}	6.5×10^{-6}	1.9×10^{-4}	6.5×10^{-6}
B (total)	4.6×10^{-6}	2.7×10^{-4}	4.6×10^{-6}	1.0×10^{-2}	4.6×10^{-6}	1.0×10^{-2}
P (total)	6.5×10^{-7}	5.3×10^{-6}	5.6×10^{-6}	5.9×10^{-6}	5.6×10^{-6}	5.9×10^{-6}
N (total)	2.0×10^{-5}	2.8×10^{-5}	2.5×10^{-6}	1.0×10^{-2}	2.5×10^{-6}	1.0×10^{-2}
Br (total)	4.3×10^{-6}	3.9×10^{-5}	4.4×10^{-6}	8.0×10^{-4}	4.4×10^{-6}	8.0×10^{-4}
I (total)	7.9×10^{-6}	5.5×10^{-6}	3.9×10^{-6}	1.8×10^{-4}	3.9×10^{-6}	1.8×10^{-4}

*Solute concentrations and ionic strength in mol/l

Table 7 Porewater chemistry within and between waste packages (Gr.1, 2, 4H) (1/3)

Rock type	Plutonic			
Groundwater	Low salinity		High salinity	
Porewater chemistry	Region I	Region II	Region I	Region II
pH	12.7	11.8 ~ 12.4	12.6 ~ 12.7	11.7 ~ 12.4
Eh (mV)	-6.0×10^{2} ~ -5.7×10^{2}	-5.6×10^{2} ~ -5.4×10^{2}	-6.0×10^{2} ~ -5.9×10^{2}	-5.7×10^{2} ~ -5.4×10^{2}
Ionic strength	3.7×10^{-1} ~ 5.3×10^{-1}	4.6×10^{-2} ~ 1.7×10^{-1}	3.8×10^{-1} ~ 5.6×10^{-1}	9.8×10^{-2} ~ 2.0×10^{-1}
Na (total)	1.4×10^{-1} ~ 3.0×10^{-1}	3.1×10^{-3} ~ 1.6×10^{-1}	1.6×10^{-1} ~ 3.4×10^{-1}	1.7×10^{-2} ~ 2.0×10^{-1}
Ca (total)	1.1×10^{-3} ~ 1.3×10^{-3}	2.5×10^{-3} ~ 1.8×10^{-2}	1.1×10^{-3} ~ 1.5×10^{-3}	2.9×10^{-3} ~ 3.2×10^{-2}
K (total)	2.2×10^{-1}	1.6×10^{-5} ~ 8.3×10^{-4}	2.2×10^{-1}	1.0×10^{-4} ~ 1.0×10^{-3}
Mg (total)	3.8×10^{-7}~4.4×10^{-7}	7.4×10^{-7} ~ 3.1×10^{-6}	3.9×10^{-7} ~ 4.8×10^{-7}	8.1×10^{-7} ~ 4.5×10^{-6}
Fe (total)	1.3×10^{-6}~3.5×10^{-6}	3.8×10^{-7} ~ 9.0×10^{-7}	2.3×10^{-6} ~ 3.5×10^{-6}	4.1×10^{-7} ~ 1.2×10^{-6}
Al (total)	4.7×10^{-5}~6.0×10^{-5}	5.4×10^{-6} ~ 2.5×10^{-5}	4.4×10^{-5} ~ 5.8×10^{-5}	4.5×10^{-6} ~ 2.3×10^{-5}
Si (total)	5.2×10^{-5}~9.2×10^{-5}	1.0×10^{-5} ~ 3.2×10^{-5}	5.0×10^{-5} ~ 9.6×10^{-5}	1.0×10^{-5} ~ 3.3×10^{-5}
S (total)	4.4×10^{-2}~8.4×10^{-2}	3.1×10^{-4} ~ 8.2×10^{-3}	3.8×10^{-2} ~ 8.4×10^{-2}	2.8×10^{-4} ~ 8.1×10^{-3}
TIC	1.5×10^{-4}~3.1×10^{-4}	8.5×10^{-6} ~ 4.7×10^{-5}	1.3×10^{-4} ~ 3.2×10^{-4}	8.3×10^{-6} ~ 4.7×10^{-5}
Cl (total)	2.3×10^{-3} ~ 4.5×10^{-3}	2.3×10^{-3} ~ 4.6×10^{-3}	4.9×10^{-2} ~ 5.1×10^{-2}	4.9×10^{-2} ~ 5.2×10^{-2}
F (total)	5.7×10^{-4}	5.7×10^{-4}	1.3×10^{-4}	1.3×10^{-4}
B (total)	4.6×10^{-6}	4.6×10^{-6} ~ 4.7×10^{-6}	2.7×10^{-4}	2.7×10^{-4} ~ 2.8×10^{-4}
P (total)	6.4×10^{-7} ~ 6.5×10^{-7}	6.5×10^{-7}	5.2×10^{-6} ~ 5.3×10^{-6}	5.3×10^{-6}
N (total)	2.0×10^{-5}	2.0×10^{-5} ~ 2.1×10^{-5}	2.8×10^{-5}	2.8×10^{-5}
Br (total)	4.3×10^{-6}	4.3×10^{-6} ~ 4.4×10^{-6}	3.9×10^{-5}	3.9×10^{-5}
I (total)	7.8×10^{-6}~ 7.9×10^{-6}	7.9×10^{-6} ~ 8.0×10^{-6}	5.5×10^{-6}	5.5×10^{-6} ~ 5.6×10^{-6}

*Solute concentrations and ionic strength in mol/l

Table 7 Porewater chemistry within and between waste packages (Gr.1, 2, 4H) (2/3)

Rock type	Neogene sediments			
Groundwater	Low salinity		High salinity	
Porewater chemistry	Region I	Region II	Region I	Region II
pH	13.2 ~ 13.3	12.3 ~ 12.9	13.2 ~ 13.3	12.3 ~ 12.8
Eh (mV)	-5.5×10^{2} ~ -5.4×10^{2}	-5.4×10^{2} ~ -5.3×10^{2}	-6.2×10^{2}	-5.9×10^{2} ~ -5.7×10^{2}
Ionic strength	3.6×10^{-1} ~ 5.2×10^{-1}	5.1×10^{-2} ~ 1.6×10^{-1}	5.7×10^{-1} ~ 6.9×10^{-1}	2.8×10^{-1}~ 3.5×10^{-1}
Na (total)	1.4×10^{-1} ~ 3.0×10^{-1}	2.8×10^{-3} ~ 1.6×10^{-1}	3.6×10^{-1} ~ 4.9×10^{-1}	2.2×10^{-1} ~ 3.5×10^{-1}
Ca (total)	7.5×10^{-4} ~ 1.0×10^{-3}	2.5×10^{-3} ~ 1.9×10^{-2}	8.8×10^{-4} ~ 1.2×10^{-3}	4.1×10^{-3} ~ 2.4×10^{-2}
K (total)	2.2×10^{-1}	3.0×10^{-5} ~ 8.4×10^{-4}	2.2×10^{-1}	1.9×10^{-3} ~ 3.2×10^{-3}
Mg (total)	2.1×10^{-7} ~ 2.7×10^{-7}	5.2×10^{-7} ~ 2.1×10^{-6}	2.4×10^{-7} ~ 3.0×10^{-7}	7.1×10^{-7} ~ 2.3×10^{-6}
Fe (total)	1.2×10^{-6} ~ 1.5×10^{-6}	7.5×10^{-7} ~ 1.1×10^{-6}	2.4×10^{-5} ~ 2.6×10^{-5}	3.5×10^{-6} ~ 8.4×10^{-6}
Al (total)	3.5×10^{-5} ~ 4.8×10^{-5}	3.7×10^{-6} ~ 1.6×10^{-5}	3.4×10^{-5} ~ 4.5×10^{-5}	4.8×10^{-6} ~ 1.4×10^{-5}
Si (total)	6.5×10^{-5} ~ 1.3×10^{-4}	1.0×10^{-5} ~ 3.2×10^{-5}	9.4×10^{-5} ~ 1.5×10^{-4}	1.6×10^{-5} ~ 3.9×10^{-5}
S (total)	1.2×10^{-2} ~ 2.7×10^{-2}	7.2×10^{-5} ~ 1.7×10^{-3}	1.5×10^{-2} ~ 2.9×10^{-2}	2.0×10^{-4} ~ 1.9×10^{-3}
TIC	1.9×10^{-4} ~ 4.6×10^{-4}	8.2×10^{-6} ~ 4.6×10^{-5}	2.6×10^{-4} ~ 5.1×10^{-4}	1.1×10^{-5} ~ 4.9×10^{-5}
Cl (total)	1.1×10^{-3} ~ 3.3×10^{-3}	1.1×10^{-3} ~ 3.3×10^{-3}	2.1×10^{-1}	2.1×10^{-1}
F (total)	1.9×10^{-4}	1.9×10^{-4}	6.5×10^{-6} ~ 6.6×10^{-6}	6.5×10^{-6} ~ 6.6×10^{-6}
B (total)	4.6×10^{-6}~ 4.7×10^{-6}	4.6×10^{-6}~ 4.7×10^{-6}	1.0×10^{-2}	1.0×10^{-2}
P (total)	5.6×10^{-6} ~ 5.7×10^{-6}	5.6×10^{-6} ~ 5.7×10^{-6}	5.9×10^{-6} ~ 6.0×10^{-6}	5.9×10^{-6} ~ 6.0×10^{-6}
N (total)	2.5×10^{-6} ~ 2.6×10^{-6}	2.5×10^{-6} ~ 2.6×10^{-6}	1.0×10^{-2}	1.0×10^{-2}
Br (total)	4.4×10^{-6} ~ 4.5×10^{-6}	4.4×10^{-6} ~ 4.5×10^{-6}	8.0×10^{-4} ~ 8.1×10^{-4}	8.0×10^{-4} ~ 8.1×10^{-4}
I (total)	3.9×10^{-6} ~ 4.0×10^{-6}	3.9×10^{-6} ~ 4.0×10^{-6}	1.8×10^{-4}	1.8×10^{-4} ~ 1.9×10^{-4}

*Solute concentrations and ionic strength in mol/l

Table 7 Porewater chemistry within and between waste packages (Gr.1, 2, 4H) (3/3)

Rock type	Pre-Neogene sediments			
Groundwater	Low salinity		High salinity	
Porewater chemistry	Region I	Region II	Region I	Region II
pH	12.7	11.8 ~ 12.4	12.6 ~ 12.7	11.8 ~ 12.3
Eh (mV)	-5.8×10^{2} ~ -5.7×10^{2}	-5.7×10^{2} ~ -5.4×10^{2}	-6.2×10^{2}	-6.0×10^{2} ~ -5.7×10^{2}
Ionic strength	3.7×10^{-1} ~ 5.3×10^{-1}	4.5×10^{-2} ~ 1.7×10^{-1}	5.7×10^{-1} ~ 7.0×10^{-1}	2.7×10^{-1} ~ 3.5×10^{-1}
Na (total)	1.4×10^{-1} ~ 3.0×10^{-1}	2.8×10^{-3} ~ 1.6×10^{-1}	3.6×10^{-1} ~ 4.8×10^{-1}	2.2×10^{-1} ~ 3.4×10^{-1}
Ca (total)	1.1×10^{-3} ~ 1.3×10^{-3}	2.5×10^{-3} ~ 1.7×10^{-2}	1.3×10^{-3} ~ 1.6×10^{-3}	4.0×10^{-3} ~ 2.2×10^{-2}
K (total)	2.2×10^{-1}	3.0×10^{-5} ~ 8.3×10^{-4}	2.2×10^{-1}	1.9×10^{-3} ~ 3.2×10^{-3}
Mg (total)	3.8×10^{-7} ~ 4.4×10^{-7}	7.3×10^{-7} ~ 3.0×10^{-6}	4.3×10^{-7} ~ 5.1×10^{-7}	1.0×10^{-6} ~ 3.3×10^{-6}
Fe (total)	1.2×10^{-6} ~ 1.9×10^{-6}	3.5×10^{-7} ~ 9.5×10^{-7}	7.1×10^{-6} ~ 7.5×10^{-6}	1.2×10^{-6} ~ 3.0×10^{-6}
Al (total)	4.7×10^{-5} ~ 6.0×10^{-5}	5.4×10^{-6} ~ 2.5×10^{-5}	4.5×10^{-5} ~ 5.5×10^{-5}	7.1×10^{-6} ~ 2.1×10^{-5}
Si (total)	5.2×10^{-5} ~ 9.2×10^{-5}	1.0×10^{-5} ~ 3.2×10^{-5}	7.5×10^{-5} ~ 1.1×10^{-4}	1.6×10^{-5} ~ 3.9×10^{-5}
S (total)	4.4×10^{-2} ~ 8.4×10^{-2}	3.2×10^{-4} ~ 8.3×10^{-3}	5.1×10^{-2} ~ 8.7×10^{-2}	9.1×10^{-4} ~ 8.6×10^{-3}
TIC	1.5×10^{-4} ~ 3.1×10^{-4}	8.5×10^{-6} ~ 4.7×10^{-5}	2.0×10^{-4} ~ 3.4×10^{-4}	1.1×10^{-5} ~ 4.9×10^{-5}
Cl (total)	1.1×10^{-3} ~ 3.3×10^{-3}	1.1×10^{-3} ~ 3.3×10^{-3}	2.1×10^{-1}	2.1×10^{-1}
F (total)	1.9×10^{-4}	1.9×10^{-4}	6.5×10^{-6}	6.5×10^{-6} ~ 6.6×10^{-6}
B (total)	4.6×10^{-6}	4.6×10^{-6} ~ 4.7×10^{-6}	1.0×10^{-2}	1.0×10^{-2}
P (total)	5.6×10^{-6}	5.6×10^{-6} ~ 5.7×10^{-6}	5.9×10^{-6}	5.9×10^{-6} ~ 6.0×10^{-6}
N (total)	2.5×10^{-6}	2.5×10^{-6} ~ 2.6×10^{-6}	1.0×10^{-2}	1.0×10^{-2}
Br (total)	4.4×10^{-6}	4.4×10^{-6} ~ 4.5×10^{-6}	7.9×10^{-4} ~ 8.0×10^{-4}	8.0×10^{-4} ~ 8.1×10^{-4}
I (total)	3.9×10^{-6}	3.9×10^{-6} ~ 4.0×10^{-6}	1.8×10^{-4}	1.8×10^{-4}

*Solute concentrations and ionic strength in mol/l

Table 8　Porewater chemistry within and between waste packages (Gr.4L) (1/2)

Rock type	Plutonic				Neogene sediments			
Groundwater	Low salinity		High salinity		Low salinity		High salinity	
Porewater chemistry	Region I	Region II	Region I	Region II	Region I	Region II	Region I	Region II
pH	12.7	11.8	12.6	11.7	13.2	12.3	13.2	12.3
Eh (mV)	-5.9×10^{2}	-5.4×10^{2}	-6.0×10^{2}	-5.5×10^{2}	-5.4×10^{2}	-5.4×10^{2}	-6.2×10^{2}	-5.7×10^{2}
Ionic strength	3.7×10^{-1}	4.7×10^{-2}	3.8×10^{-1}	1.0×10^{-1}	3.6×10^{-1}	5.1×10^{-2}	5.7×10^{-1}	2.8×10^{-1}
Na (total)	1.4×10^{-1}	3.1×10^{-3}	1.6×10^{-1}	1.7×10^{-2}	1.4×10^{-1}	2.8×10^{-3}	3.6×10^{-1}	2.2×10^{-1}
Ca (total)	1.3×10^{-3}	1.8×10^{-2}	1.5×10^{-3}	3.2×10^{-2}	1.0×10^{-3}	1.9×10^{-2}	1.2×10^{-3}	2.4×10^{-2}
K (total)	2.2×10^{-1}	1.6×10^{-5}	2.2×10^{-1}	1.0×10^{-4}	2.2×10^{-1}	3.0×10^{-5}	2.2×10^{-1}	3.2×10^{-3}
Mg (total)	4.4×10^{-7}	3.1×10^{-6}	4.8×10^{-7}	4.5×10^{-6}	2.7×10^{-7}	2.1×10^{-6}	3.0×10^{-7}	2.3×10^{-6}
Fe (total)	2.6×10^{-6}	4.0×10^{-7}	3.5×10^{-6}	4.3×10^{-7}	1.3×10^{-6}	7.8×10^{-7}	2.4×10^{-5}	3.5×10^{-6}
Al (total)	4.7×10^{-5}	5.4×10^{-6}	4.4×10^{-5}	4.5×10^{-6}	3.5×10^{-5}	3.7×10^{-6}	3.4×10^{-5}	4.8×10^{-6}
Si (total)	5.2×10^{-5}	1.0×10^{-5}	5.0×10^{-5}	1.0×10^{-5}	6.5×10^{-5}	1.0×10^{-5}	9.4×10^{-5}	1.6×10^{-5}
S (total)	4.4×10^{-2}	3.1×10^{-4}	3.8×10^{-2}	2.8×10^{-4}	1.2×10^{-2}	7.2×10^{-5}	1.5×10^{-2}	2.0×10^{-4}
TIC	1.5×10^{-4}	8.5×10^{-6}	1.3×10^{-4}	8.3×10^{-6}	1.9×10^{-4}	8.2×10^{-6}	2.6×10^{-4}	1.1×10^{-5}
Cl (total)	2.3×10^{-3}	2.3×10^{-3}	4.9×10^{-2}	4.9×10^{-2}	1.1×10^{-3}	1.1×10^{-3}	2.1×10^{-1}	2.1×10^{-1}
F (total)	5.7×10^{-4}	5.7×10^{-4}	1.3×10^{-4}	1.3×10^{-4}	1.9×10^{-4}	1.9×10^{-4}	6.5×10^{-6}	6.5×10^{-6}
B (total)	4.6×10^{-6}	4.6×10^{-6}	2.7×10^{-4}	2.7×10^{-4}	4.6×10^{-6}	4.6×10^{-6}	1.0×10^{-2}	1.0×10^{-2}
P (total)	6.4×10^{-7}	6.5×10^{-7}	5.2×10^{-6}	5.3×10^{-6}	5.6×10^{-6}	5.6×10^{-6}	5.9×10^{-6}	5.9×10^{-6}
N (total)	2.0×10^{-5}	2.0×10^{-5}	2.8×10^{-5}	2.8×10^{-5}	2.5×10^{-6}	2.5×10^{-6}	1.0×10^{-2}	1.0×10^{-2}
Br (total)	4.3×10^{-6}	4.3×10^{-6}	3.9×10^{-5}	3.9×10^{-5}	4.4×10^{-6}	4.4×10^{-6}	8.0×10^{-4}	8.0×10^{-4}
I (total)	7.8×10^{-6}	7.9×10^{-6}	5.5×10^{-6}	5.5×10^{-6}	3.9×10^{-6}	3.9×10^{-6}	1.8×10^{-4}	1.8×10^{-4}

*Solute concentrations and ionic strength in mol/l

Table 8 Porewater chemistry within and between waste interpackage fillers (Gr.4L) (2/2)

Rock type	Pre-Neogene sediments			
Groundwater	Low salinity		High salinity	
Porewater chemistry	Region I	Region II	Region I	Region II
pH	12.7	11.8	12.6	11.8
Eh (mV)	-5.7×10^{2}	-5.4×10^{2}	-6.2×10^{2}	-5.7×10^{2}
Ionic strength	3.7×10^{-1}	4.5×10^{-2}	5.7×10^{-1}	2.7×10^{-1}
Na (total)	1.4×10^{-1}	2.8×10^{-3}	3.6×10^{-1}	2.2×10^{-1}
Ca (total)	1.3×10^{-3}	1.7×10^{-2}	1.6×10^{-3}	2.2×10^{-2}
K (total)	2.2×10^{-1}	3.0×10^{-5}	2.2×10^{-1}	3.2×10^{-3}
Mg (total)	4.4×10^{-7}	3.0×10^{-6}	5.1×10^{-7}	3.3×10^{-6}
Fe (total)	1.3×10^{-6}	3.6×10^{-7}	7.1×10^{-6}	1.2×10^{-6}
Al (total)	4.7×10^{-5}	5.4×10^{-6}	4.5×10^{-5}	7.1×10^{-6}
Si (total)	5.2×10^{-5}	1.0×10^{-5}	7.5×10^{-5}	1.6×10^{-5}
S (total)	4.4×10^{-2}	3.2×10^{-4}	5.1×10^{-2}	9.1×10^{-4}
TIC	1.5×10^{-4}	8.5×10^{-6}	2.0×10^{-4}	1.1×10^{-5}
Cl (total)	1.1×10^{-3}	1.1×10^{-3}	2.1×10^{-1}	2.1×10^{-1}
F (total)	1.9×10^{-4}	1.9×10^{-4}	6.5×10^{-6}	6.5×10^{-6}
B (total)	4.6×10^{-6}	4.6×10^{-6}	1.0×10^{-2}	1.0×10^{-2}
P (total)	5.6×10^{-6}	5.6×10^{-6}	5.9×10^{-6}	5.9×10^{-6}
N (total)	2.5×10^{-6}	2.5×10^{-6}	1.0×10^{-2}	1.0×10^{-2}
Br (total)	4.4×10^{-6}	4.4×10^{-6}	7.9×10^{-4}	8.0×10^{-4}
I (total)	3.9×10^{-6}	3.9×10^{-6}	1.8×10^{-4}	1.8×10^{-4}

*Solute concentrations and ionic strength in mol/l

Table 9 Solubility and solubility limiting solid phases (Plutonic repository) (1/3)

Analysis case	Base case									
Repository	HLW			TRU	Gr.1, 4H		Gr.2		Gr.4L	
	Solubility limited solid phase	Solubility (mol/l)		Solubility limited solid phase	Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)	
Groundwater		Low salinity	High salinity		Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	$CaCO_3$ (calcite)	8×10^{-3}	5×10^{-3}	(Not assessed)	—		—		—	
C (organic)	(Not assessed)	—		Not set	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cl	Not set	Soluble	Soluble	Not set	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Co	(Not assessed)	—		beta-$Co(OH)_2$	4×10^{-6}	4×10^{-6}	4×10^{-6}	4×10^{-6}	4×10^{-6}	4×10^{-6}
Ni	(Not assessed)	—		beta-$Ni(OH)_2$	6×10^{-6}	6×10^{-6}	6×10^{-6}	6×10^{-6}	5×10^{-6}	5×10^{-6}
Se	$FeSe_2$(cr)	3×10^{-8}	1×10^{-8}	$FeSe_2$(cr)	4×10^{-6}	5×10^{-6}	4×10^{-6}	5×10^{-6}	2×10^{-6}	5×10^{-6}
Sr	$SrCO_3$(strontianite)	4×10^{-4}	4×10^{-4}	$SrCO_3$(strontianite)	9×10^{-5}	1×10^{-4}	9×10^{-5}	1×10^{-4}	9×10^{-5}	1×10^{-4}
Zr	$Zr(OH)_4$(am,fresh)	1×10^{-8}	1×10^{-8}	$Zr(OH)_4$(am,fresh)	1×10^{-7}	2×10^{-7}	1×10^{-7}	2×10^{-7}	8×10^{-8}	2×10^{-7}
Nb	Nb_2O_5(s)	2×10^{-5}	1×10^{-6}	Nb_2O_5(s)	3×10^{-2}	3×10^{-2}	3×10^{-2}	3×10^{-2}	2×10^{-2}	2×10^{-2}
Mo	(Not assessed)	—		$CaMoO_4$(cr)	4×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}	2×10^{-4}	2×10^{-4}
Tc	$TcO_2\cdot1.6H_2O$(s)	5×10^{-9}	5×10^{-9}	$TcO_2\cdot1.6H_2O$(s)	4×10^{-7}	4×10^{-7}	4×10^{-7}	4×10^{-7}	4×10^{-7}	3×10^{-7}
Pd	(Not assessed)	—		$Pd(OH)_2$(am)	9×10^{-7}	9×10^{-7}	9×10^{-7}	9×10^{-7}	7×10^{-7}	7×10^{-7}
Sn	SnO_2(am)	6×10^{-6}	7×10^{-7}	SnO_2(am)	4×10^{-2}	4×10^{-2}	4×10^{-2}	4×10^{-2}	3×10^{-2}	3×10^{-2}
I	Not set	Soluble	Soluble	Not set	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cs	Not set	Soluble	Soluble	Not set	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Pb	$PbCO_3$(cerussite)	2×10^{-6}	4×10^{-6}	$Pb(OH)_2$(am)	6×10^{-2}	6×10^{-2}	6×10^{-2}	6×10^{-2}	5×10^{-2}	5×10^{-2}
Ra	$RaCO_3$(cr)	8×10^{-4}	8×10^{-4}	$RaCO_3$(cr)	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}	4×10^{-4}	4×10^{-4}
Ac	$AcCO_3OH$(am)	2×10^{-5}	3×10^{-5}	$Ac(OH)_3$(am)	7×10^{-10}	7×10^{-10}	9×10^{-10}	9×10^{-10}	7×10^{-10}	7×10^{-10}
Th	ThO_2(am,aged)	4×10^{-8}	2×10^{-8}	ThO_2(am,aged)	2×10^{-9}	2×10^{-9}	2×10^{-9}	2×10^{-9}	2×10^{-9}	2×10^{-9}
Pa	Pa_2O_5(s)	2×10^{-9}	2×10^{-9}	Pa_2O_5(s)	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}
U	UO_2(am)	2×10^{-6}	6×10^{-7}	UO_2(am)	5×10^{-7}	5×10^{-7}	5×10^{-7}	5×10^{-7}	3×10^{-7}	1×10^{-7}
Np	NpO_2(am)	2×10^{-8}	8×10^{-9}	NpO_2(am)	1×10^{-9}	1×10^{-9}	5×10^{-9}	5×10^{-9}	1×10^{-9}	1×10^{-9}
Pu	PuO_2(am)	2×10^{-8}	3×10^{-8}	PuO_2(am)	2×10^{-11}	2×10^{-11}	2×10^{-9}	2×10^{-9}	2×10^{-11}	2×10^{-11}
Am	$AmCO_3OH\cdot0.5H_2O$(cr)	2×10^{-7}	4×10^{-7}	$Am(OH)_3$(cr)	4×10^{-11}	4×10^{-11}	5×10^{-11}	5×10^{-11}	4×10^{-11}	4×10^{-11}
Cm	$CmCO_3OH\cdot0.5H_2O$(cr)	2×10^{-7}	4×10^{-7}	$Cm(OH)_3$(cr)	4×10^{-11}	4×10^{-11}	5×10^{-11}	5×10^{-11}	4×10^{-11}	4×10^{-11}

Table 9 Solubility and solubility limiting solid phases (Plutonic repository) (2/3)

Analysis case	Thermal increase in solubility – Variant case							
Repository	HLW		Gr.1, 4H		Gr.2		Gr.4L	
	Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	8×10^{-1}	5×10^{-1}	(Not assessed)		(Not assessed)		(Not assessed)	
C (organic)	(Not assessed)		Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cl	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Co	(Not assessed)		4×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}
Ni	(Not assessed)		6×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}	5×10^{-4}	5×10^{-4}
Se	3×10^{-6}	1×10^{-6}	4×10^{-4}	5×10^{-4}	4×10^{-4}	5×10^{-4}	2×10^{-4}	5×10^{-4}
Sr	4×10^{-2}	4×10^{-2}	9×10^{-3}	1×10^{-2}	9×10^{-3}	1×10^{-2}	9×10^{-3}	1×10^{-2}
Zr	1×10^{-6}	1×10^{-6}	1×10^{-5}	2×10^{-5}	1×10^{-5}	2×10^{-5}	8×10^{-6}	2×10^{-5}
Nb	2×10^{-3}	1×10^{-4}	3	3	3	3	2	2
Mo	(Not assessed)		4×10^{-2}	4×10^{-2}	4×10^{-2}	4×10^{-2}	2×10^{-2}	2×10^{-2}
Tc	5×10^{-7}	5×10^{-7}	4×10^{-5}	4×10^{-5}	4×10^{-5}	4×10^{-5}	4×10^{-5}	3×10^{-5}
Pd	(Not assessed)		9×10^{-5}	9×10^{-5}	9×10^{-5}	9×10^{-5}	7×10^{-5}	7×10^{-5}
Sn	6×10^{-4}	7×10^{-5}	4	4	4	4	3	3
I	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cs	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Pb	2×10^{-4}	4×10^{-4}	6	6	6	6	5	5
Ra	8×10^{-2}	8×10^{-2}	5×10^{-2}	5×10^{-2}	5×10^{-2}	5×10^{-2}	4×10^{-2}	4×10^{-2}
Ac	2×10^{-3}	3×10^{-3}	7×10^{-8}	7×10^{-8}	9×10^{-8}	9×10^{-8}	7×10^{-8}	7×10^{-8}
Th	4×10^{-6}	2×10^{-6}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}
Pa	2×10^{-7}	2×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}
U	2×10^{-4}	6×10^{-5}	5×10^{-5}	5×10^{-5}	5×10^{-5}	5×10^{-5}	3×10^{-5}	1×10^{-5}
Np	2×10^{-6}	8×10^{-7}	1×10^{-7}	1×10^{-7}	5×10^{-7}	5×10^{-7}	1×10^{-7}	1×10^{-7}
Pu	2×10^{-6}	3×10^{-6}	2×10^{-9}	2×10^{-9}	2×10^{-7}	2×10^{-7}	2×10^{-9}	2×10^{-9}
Am	2×10^{-5}	4×10^{-5}	4×10^{-9}	4×10^{-9}	5×10^{-9}	5×10^{-9}	4×10^{-9}	4×10^{-9}
Cm	2×10^{-5}	4×10^{-5}	4×10^{-9}	4×10^{-9}	5×10^{-9}	5×10^{-9}	4×10^{-9}	4×10^{-9}

Table 9 Solubility and solubility limiting solid phases (Plutonic repository) (3/3)

Analysis case	Uncertainty in thermodynamic data - Variant case							
Repository	HLW		Gr.1, 4H		Gr.2		Gr.4L	
	Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	8×10^{-3}	5×10^{-3}	(Not assessed)		(Not assessed)		(Not assessed)	
C (organic)	(Not assessed)		Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cl	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Co	(Not assessed)		8×10^{-6}	8×10^{-6}	8×10^{-6}	8×10^{-6}	8×10^{-6}	8×10^{-6}
Ni	(Not assessed)		2×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}
Se	3×10^{-6}	2×10^{-6}	3×10^{-5}	3×10^{-5}	3×10^{-5}	3×10^{-5}	2×10^{-5}	3×10^{-5}
Sr	4×10^{-4}	4×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}	9×10^{-5}	1×10^{-4}
Zr	2×10^{-8}	2×10^{-8}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}
Nb	5×10^{-5}	4×10^{-6}	5×10^{-2}	5×10^{-2}	5×10^{-2}	5×10^{-2}	4×10^{-2}	4×10^{-2}
Mo	(Not assessed)		4×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}	3×10^{-4}	3×10^{-4}
Tc	2×10^{-8}	1×10^{-8}	1×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}	8×10^{-7}	7×10^{-7}
Pd	(Not assessed)		5×10^{-6}	5×10^{-6}	5×10^{-6}	5×10^{-6}	4×10^{-6}	4×10^{-6}
Sn	4×10^{-5}	6×10^{-6}	4×10^{-2}	4×10^{-2}	4×10^{-2}	4×10^{-2}	3×10^{-2}	3×10^{-2}
I	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cs	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Pb	2×10^{-6}	4×10^{-6}	6×10^{-2}	6×10^{-2}	6×10^{-2}	6×10^{-2}	5×10^{-2}	5×10^{-2}
Ra	2×10^{-3}	2×10^{-3}	8×10^{-4}	8×10^{-4}	8×10^{-4}	8×10^{-4}	6×10^{-4}	6×10^{-4}
Ac	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Th	3×10^{-6}	9×10^{-7}	8×10^{-8}	8×10^{-8}	8×10^{-8}	8×10^{-8}	8×10^{-8}	8×10^{-8}
Pa	2×10^{-9}	2×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}
U	4×10^{-5}	3×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}	1×10^{-5}	9×10^{-6}
Np	2×10^{-6}	8×10^{-7}	1×10^{-7}	1×10^{-7}	5×10^{-7}	5×10^{-7}	1×10^{-7}	1×10^{-7}
Pu	2×10^{-7}	3×10^{-7}	2×10^{-10}	2×10^{-10}	3×10^{-8}	3×10^{-8}	2×10^{-10}	2×10^{-10}
Am	2×10^{-6}	4×10^{-6}	5×10^{-10}	6×10^{-10}	7×10^{-10}	7×10^{-10}	5×10^{-10}	6×10^{-10}
Cm	2×10^{-6}	4×10^{-6}	5×10^{-10}	6×10^{-10}	7×10^{-10}	7×10^{-10}	5×10^{-10}	6×10^{-10}

Table 10 Solubility and solubility limiting solid phases (Neogene repository) (1/3)

Analysis case	Base case									
Repository	HLW			TRU	Gr.1, 4H		Gr.2		Gr.4L	
	Solubility limited solid phase	Solubility (mol/l)		Solubility limited solid phase	Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)	
Groundwater		Low salinity	High salinity		Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	$CaCO_3$(calcite)	1×10^{-2}	4×10^{-2}	(Not assessed)	—		—		—	
C (organic)	(Not assessed)	—		Not set	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cl	Not set	Soluble	Soluble	Not set	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Co	(Not assessed)	—		beta-$Co(OH)_2$	6×10^{-6}	1×10^{-5}	6×10^{-6}	1×10^{-5}	5×10^{-6}	1×10^{-5}
Ni	(Not assessed)	—		beta-$Ni(OH)_2$	2×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}
Se	$FeSe_2$(cr)	3×10^{-8}	5×10^{-11}	$FeSe_2$(cr)	2×10^{-6}	3×10^{-5}	2×10^{-6}	3×10^{-5}	7×10^{-7}	3×10^{-5}
Sr	$SrCO_3$(strontianite)	4×10^{-4}	2×10^{-3}	$SrCO_3$(strontianite)	1×10^{-4}	2×10^{-4}	1×10^{-4}	2×10^{-4}	8×10^{-5}	2×10^{-4}
Zr	$Zr(OH)_4$(am,fresh)	1×10^{-8}	8×10^{-8}	$Zr(OH)_4$(am,fresh)	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	6×10^{-7}	9×10^{-7}
Nb	Nb_2O_5(s)	3×10^{-5}	4×10^{-8}	Nb_2O_5(s)	8×10^{-2}	8×10^{-2}	8×10^{-2}	8×10^{-2}	6×10^{-2}	6×10^{-2}
Mo	(Not assessed)	—		$CaMoO_4$(cr)	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}	3×10^{-4}	4×10^{-4}
Tc	$TcO_2\cdot1.6H_2O$(s)	5×10^{-9}	3×10^{-8}	$TcO_2\cdot1.6H_2O$(s)	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}
Pd	(Not assessed)	—		$Pd(OH)_2$(am)	3×10^{-6}	6×10^{-4}	3×10^{-6}	6×10^{-4}	3×10^{-6}	6×10^{-4}
Sn	SnO_2(am)	9×10^{-6}	4×10^{-7}	SnO_2(am)	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	1×10^{-1}	1×10^{-1}
I	Not set	Soluble	Soluble	Not set	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cs	Not set	Soluble	Soluble	Not set	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Pb	$PbCO_3$(cerussite)	3×10^{-6}	3×10^{-6}	$Pb(OH)_2$(am)	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Ra	$RaCO_3$(cr)	8×10^{-4}	6×10^{-3}	$RaCO_3$(cr)	3×10^{-4}	4×10^{-4}	3×10^{-4}	4×10^{-4}	3×10^{-4}	4×10^{-4}
Ac	$AcCO_3OH$(am)	2×10^{-5}	9×10^{-5}	$Ac(OH)_3$(am)	6×10^{-10}	6×10^{-10}	9×10^{-10}	9×10^{-10}	6×10^{-10}	6×10^{-10}
Th	ThO_2(am,aged)	5×10^{-8}	7×10^{-7}	ThO_2(am,aged)	2×10^{-9}	2×10^{-9}	2×10^{-9}	2×10^{-9}	2×10^{-9}	2×10^{-9}
Pa	Pa_2O_5(s)	2×10^{-9}	8×10^{-9}	Pa_2O_5(s)	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}
U	UO_2(am)	3×10^{-6}	3×10^{-5}	UO_2(am)	2×10^{-6}	1×10^{-6}	2×10^{-6}	1×10^{-6}	2×10^{-6}	4×10^{-7}
Np	NpO_2(am)	3×10^{-8}	4×10^{-7}	NpO_2(am)	1×10^{-9}	1×10^{-9}	5×10^{-9}	5×10^{-9}	1×10^{-9}	1×10^{-9}
Pu	PuO_2(am)	2×10^{-8}	4×10^{-7}	PuO_2(am)	2×10^{-11}	2×10^{-11}	2×10^{-9}	2×10^{-9}	2×10^{-11}	2×10^{-11}
Am	$AmCO_3OH\cdot0.5H_2O$(cr)	8×10^{-8}	6×10^{-7}	$Am(OH)_3$(cr)	3×10^{-11}	3×10^{-11}	5×10^{-11}	4×10^{-11}	3×10^{-11}	3×10^{-11}
Cm	$CmCO_3OH\cdot0.5H_2O$(cr)	8×10^{-8}	6×10^{-7}	$Cm(OH)_3$(cr)	3×10^{-11}	3×10^{-11}	5×10^{-11}	4×10^{-11}	3×10^{-11}	3×10^{-11}

Table 10　Solubility and solubility limiting solid phases (Neogene repository) (2/3)

Analysis case	Thermal increase in solubility - Variant case							
Repository	HLW		Gr.1, 4H		Gr.2		Gr.4L	
	Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	1	4	(Not assessed)		(Not assessed)		(Not assessed)	
C (organic)	(Not assessed)		Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cl	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Co	(Not assessed)		6×10^{-4}	1×10^{-3}	6×10^{-4}	1×10^{-3}	5×10^{-4}	1×10^{-3}
Ni	(Not assessed)		2×10^{-3}	2×10^{-3}	2×10^{-3}	2×10^{-3}	2×10^{-3}	2×10^{-3}
Se	3×10^{-6}	5×10^{-9}	2×10^{-4}	3×10^{-3}	2×10^{-4}	3×10^{-3}	7×10^{-5}	3×10^{-3}
Sr	4×10^{-2}	2×10^{-1}	1×10^{-2}	2×10^{-2}	1×10^{-2}	2×10^{-2}	8×10^{-3}	2×10^{-2}
Zr	1×10^{-6}	8×10^{-6}	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}	6×10^{-5}	9×10^{-5}
Nb	3×10^{-3}	4×10^{-6}	8	8	8	8	6	6
Mo	(Not assessed)		5×10^{-2}	5×10^{-2}	5×10^{-2}	5×10^{-2}	3×10^{-2}	4×10^{-2}
Tc	5×10^{-7}	3×10^{-6}	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}
Pd	(Not assessed)		3×10^{-4}	6×10^{-2}	3×10^{-4}	6×10^{-2}	3×10^{-4}	6×10^{-2}
Sn	9×10^{-4}	4×10^{-5}	2×10	2×10	2×10	2×10	1×10	1×10
I	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cs	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Pb	3×10^{-4}	3×10^{-4}	2×10	2×10	2×10	2×10	2×10	2×10
Ra	8×10^{-2}	6×10^{-1}	3×10^{-2}	4×10^{-2}	3×10^{-2}	4×10^{-2}	3×10^{-2}	4×10^{-2}
Ac	2×10^{-3}	9×10^{-3}	6×10^{-8}	6×10^{-8}	9×10^{-8}	9×10^{-8}	6×10^{-8}	6×10^{-8}
Th	5×10^{-6}	7×10^{-5}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}
Pa	2×10^{-7}	8×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}
U	3×10^{-4}	3×10^{-3}	2×10^{-4}	1×10^{-4}	2×10^{-4}	1×10^{-4}	2×10^{-4}	4×10^{-5}
Np	3×10^{-6}	4×10^{-5}	1×10^{-7}	1×10^{-7}	5×10^{-7}	5×10^{-7}	1×10^{-7}	1×10^{-7}
Pu	2×10^{-6}	4×10^{-5}	2×10^{-9}	2×10^{-9}	2×10^{-7}	2×10^{-7}	2×10^{-9}	2×10^{-9}
Am	8×10^{-6}	6×10^{-5}	3×10^{-9}	3×10^{-9}	5×10^{-9}	4×10^{-9}	3×10^{-9}	3×10^{-9}
Cm	8×10^{-6}	6×10^{-5}	3×10^{-9}	3×10^{-9}	5×10^{-9}	4×10^{-9}	3×10^{-9}	3×10^{-9}

Table 10 Solubility and solubility limiting solid phases (Neogene repository) (3/3)

Analysis case	Uncertainty in thermodynamic data - Variant case							
Repository	HLW		Gr.1, 4H		Gr.2		Gr.4L	
	Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	1×10^{-2}	4×10^{-2}	(Not assessed)		(Not assessed)		(Not assessed)	
C (organic)	(Not assessed)		Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cl	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Co	(Not assessed)		2×10^{-5}	2×10^{-5}	2×10^{-5}	2×10^{-5}	1×10^{-5}	2×10^{-5}
Ni	(Not assessed)		8×10^{-5}	8×10^{-5}	8×10^{-5}	8×10^{-5}	6×10^{-5}	6×10^{-5}
Se	1×10^{-6}	3×10^{-8}	2×10^{-4}	3×10^{-4}	2×10^{-4}	3×10^{-4}	8×10^{-5}	3×10^{-4}
Sr	4×10^{-4}	2×10^{-3}	1×10^{-4}	2×10^{-4}	1×10^{-4}	2×10^{-4}	9×10^{-5}	2×10^{-4}
Zr	2×10^{-8}	2×10^{-7}	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	1×10^{-6}	2×10^{-6}
Nb	8×10^{-5}	2×10^{-7}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Mo	(Not assessed)		6×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}	4×10^{-4}	4×10^{-4}
Tc	2×10^{-8}	5×10^{-8}	4×10^{-6}	4×10^{-6}	4×10^{-6}	4×10^{-6}	3×10^{-6}	3×10^{-6}
Pd	(Not assessed)		2×10^{-5}	1×10^{-3}	2×10^{-5}	1×10^{-3}	2×10^{-5}	1×10^{-3}
Sn	7×10^{-5}	3×10^{-6}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	1×10^{-1}	1×10^{-1}
I	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cs	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Pb	3×10^{-6}	3×10^{-6}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Ra	2×10^{-3}	8×10^{-3}	6×10^{-4}	8×10^{-4}	6×10^{-4}	8×10^{-4}	5×10^{-4}	7×10^{-4}
Ac	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Th	3×10^{-6}	5×10^{-5}	8×10^{-8}	8×10^{-8}	8×10^{-8}	8×10^{-8}	8×10^{-8}	8×10^{-8}
Pa	2×10^{-9}	8×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}
U	8×10^{-5}	7×10^{-4}	8×10^{-5}	7×10^{-5}	8×10^{-5}	7×10^{-5}	4×10^{-5}	4×10^{-5}
Np	3×10^{-6}	4×10^{-5}	1×10^{-7}	1×10^{-7}	5×10^{-7}	5×10^{-7}	1×10^{-7}	1×10^{-7}
Pu	2×10^{-7}	3×10^{-6}	2×10^{-10}	2×10^{-10}	3×10^{-8}	3×10^{-8}	2×10^{-10}	2×10^{-10}
Am	8×10^{-7}	6×10^{-6}	5×10^{-10}	5×10^{-10}	7×10^{-10}	7×10^{-10}	5×10^{-10}	5×10^{-10}
Cm	8×10^{-7}	6×10^{-6}	5×10^{-10}	5×10^{-10}	7×10^{-10}	7×10^{-10}	5×10^{-10}	5×10^{-10}

Table 11 Solubility and solubility limiting solid phases (Pre-Neogene repository) (1/3)

Analysis case	Base case									
Repository	HLW			TRU	Gr.1, 4H		Gr.2		Gr.4L	
	Solubility limited solid phase	Solubility (mol/l)		Solubility limited solid phase	Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)	
Groundwater		Low salinity	High salinity		Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	$CaCO_3$(calcite)	9×10^{-3}	5×10^{-2}	(Not assessed)	—		—		—	
C (organic)	(Not assessed)	—		Not set	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cl	Not set	Soluble	Soluble	Not set	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Co	(Not assessed)	—		beta-$Co(OH)_2$	4×10^{-6}	3×10^{-4}	4×10^{-6}	3×10^{-4}	4×10^{-6}	3×10^{-4}
Ni	(Not assessed)	—		beta-$Ni(OH)_2$	6×10^{-6}	4×10^{-5}	6×10^{-6}	4×10^{-5}	5×10^{-6}	4×10^{-5}
Se	$FeSe_2$(cr)	3×10^{-8}	8×10^{-11}	$FeSe_2$(cr)	2×10^{-6}	8×10^{-6}	2×10^{-6}	8×10^{-6}	9×10^{-7}	7×10^{-6}
Sr	$SrCO_3$(strontianite)	4×10^{-4}	3×10^{-3}	$SrCO_3$(strontianite)	9×10^{-5}	2×10^{-4}	9×10^{-5}	2×10^{-4}	9×10^{-5}	2×10^{-4}
Zr	$Zr(OH)_4$(am,fresh)	1×10^{-8}	8×10^{-8}	$Zr(OH)_4$(am,fresh)	1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}	8×10^{-8}	1×10^{-7}
Nb	Nb_2O_5(s)	2×10^{-5}	4×10^{-8}	Nb_2O_5(s)	3×10^{-2}	2×10^{-2}	3×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}
Mo	(Not assessed)	—		$CaMoO_4$(cr)	4×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}	2×10^{-4}	3×10^{-4}
Tc	$TcO_2\cdot1.6H_2O$(s)	5×10^{-9}	4×10^{-8}	$TcO_2\cdot1.6H_2O$(s)	4×10^{-7}	4×10^{-7}	4×10^{-7}	4×10^{-7}	4×10^{-7}	4×10^{-7}
Pd	(Not assessed)	—		$Pd(OH)_2$(am)	9×10^{-7}	2×10^{-3}	9×10^{-7}	2×10^{-3}	7×10^{-7}	2×10^{-3}
Sn	SnO_2(am)	5×10^{-6}	4×10^{-7}	SnO_2(am)	4×10^{-2}	3×10^{-2}	4×10^{-2}	3×10^{-2}	3×10^{-2}	3×10^{-2}
I	Not set	Soluble	Soluble	Not set	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cs	Not set	Soluble	Soluble	Not set	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Pb	$PbCO_3$(cerussite)	2×10^{-6}	4×10^{-6}	$Pb(OH)_2$(am)	6×10^{-2}	5×10^{-2}	6×10^{-2}	5×10^{-2}	5×10^{-2}	5×10^{-2}
Ra	$RaCO_3$(cr)	9×10^{-4}	8×10^{-3}	$RaCO_3$(cr)	5×10^{-4}	6×10^{-4}	5×10^{-4}	6×10^{-4}	4×10^{-4}	5×10^{-4}
Ac	$AcCO_3OH$(am)	2×10^{-5}	2×10^{-4}	$Ac(OH)_3$(am)	7×10^{-10}	7×10^{-10}	9×10^{-10}	9×10^{-10}	7×10^{-10}	7×10^{-10}
Th	ThO_2(am,aged)	4×10^{-8}	7×10^{-7}	ThO_2(am,aged)	2×10^{-9}	2×10^{-9}	2×10^{-9}	2×10^{-9}	2×10^{-9}	2×10^{-9}
Pa	Pa_2O_5(s)	2×10^{-9}	2×10^{-8}	Pa_2O_5(s)	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}
U	UO_2(am)	2×10^{-6}	2×10^{-5}	UO_2(am)	5×10^{-7}	7×10^{-8}	5×10^{-7}	7×10^{-8}	3×10^{-7}	4×10^{-8}
Np	NpO_2(am)	2×10^{-8}	4×10^{-7}	NpO_2(am)	1×10^{-9}	1×10^{-9}	5×10^{-9}	5×10^{-9}	1×10^{-9}	1×10^{-9}
Pu	PuO_2(am)	2×10^{-8}	3×10^{-5}	PuO_2(am)	2×10^{-11}	2×10^{-11}	2×10^{-9}	2×10^{-9}	2×10^{-11}	2×10^{-11}
Am	$AmCO_3OH\cdot0.5H_2O$(cr)	2×10^{-7}	2×10^{-6}	$Am(OH)_3$(cr)	4×10^{-11}	4×10^{-11}	5×10^{-11}	5×10^{-11}	4×10^{-11}	4×10^{-11}
Cm	$CmCO_3OH\cdot0.5H_2O$(cr)	2×10^{-7}	2×10^{-6}	$Cm(OH)_3$(cr)	4×10^{-11}	4×10^{-11}	5×10^{-11}	5×10^{-11}	4×10^{-11}	4×10^{-11}

Table 11 Solubility and solubility limiting solid phases (Pre-Neogene repository) (2/3)

Analysis case	Thermal increase in solubility - Variant case							
Repository	HLW		Gr.1, 4H		Gr.2		Gr.4L	
	Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	9×10^{-1}	5	(Not assessed)		(Not assessed)		(Not assessed)	
C (organic)	(Not assessed)		Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cl	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Co	(Not assessed)		4×10^{-4}	3×10^{-2}	4×10^{-4}	3×10^{-2}	4×10^{-4}	3×10^{-2}
Ni	(Not assessed)		6×10^{-4}	4×10^{-3}	6×10^{-4}	4×10^{-3}	5×10^{-4}	4×10^{-3}
Se	3×10^{-6}	8×10^{-9}	2×10^{-4}	8×10^{-4}	2×10^{-4}	8×10^{-4}	9×10^{-5}	7×10^{-4}
Sr	4×10^{-2}	3×10^{-1}	9×10^{-3}	2×10^{-2}	9×10^{-3}	2×10^{-2}	9×10^{-3}	2×10^{-2}
Zr	1×10^{-6}	8×10^{-6}	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-5}	8×10^{-6}	1×10^{-5}
Nb	2×10^{-3}	4×10^{-6}	3	2	3	2	2	2
Mo	(Not assessed)		4×10^{-2}	4×10^{-2}	4×10^{-2}	4×10^{-2}	2×10^{-2}	3×10^{-2}
Tc	5×10^{-7}	4×10^{-6}	4×10^{-5}	4×10^{-5}	4×10^{-5}	4×10^{-5}	4×10^{-5}	4×10^{-5}
Pd	(Not assessed)		9×10^{-5}	2×10^{-1}	9×10^{-5}	2×10^{-1}	7×10^{-5}	2×10^{-1}
Sn	5×10^{-4}	4×10^{-5}	4	3	4	3	3	3
I	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cs	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Pb	2×10^{-4}	4×10^{-4}	6	5	6	5	5	5
Ra	9×10^{-2}	8×10^{-1}	5×10^{-2}	6×10^{-2}	5×10^{-2}	6×10^{-2}	4×10^{-2}	5×10^{-2}
Ac	2×10^{-3}	2×10^{-2}	7×10^{-8}	7×10^{-8}	9×10^{-8}	9×10^{-8}	7×10^{-8}	7×10^{-8}
Th	4×10^{-6}	7×10^{-5}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}
Pa	2×10^{-7}	2×10^{-6}	1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}	1×10^{-7}
U	2×10^{-4}	2×10^{-3}	5×10^{-5}	7×10^{-6}	5×10^{-5}	7×10^{-6}	3×10^{-5}	4×10^{-6}
Np	2×10^{-6}	4×10^{-5}	1×10^{-7}	1×10^{-7}	5×10^{-7}	5×10^{-7}	1×10^{-7}	1×10^{-7}
Pu	2×10^{-6}	3×10^{-3}	2×10^{-9}	2×10^{-9}	2×10^{-7}	2×10^{-7}	2×10^{-9}	2×10^{-9}
Am	2×10^{-5}	2×10^{-4}	4×10^{-9}	4×10^{-9}	5×10^{-9}	5×10^{-9}	4×10^{-9}	4×10^{-9}
Cm	2×10^{-5}	2×10^{-4}	4×10^{-9}	4×10^{-9}	5×10^{-9}	5×10^{-9}	4×10^{-9}	4×10^{-9}

Table 10 Solubility and solubility limiting solid phases (Pre-Neogene repository) (3/3)

Analysis case	Uncertainty in thermodynamic data - Variant case							
Repository	HLW		Gr.1, 4H		Gr.2		Gr.4L	
	Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)		Solubility (mol/l)	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	9×10^{-3}	5×10^{-2}	(Not assessed)		(Not assessed)		(Not assessed)	
C (organic)	(Not assessed)		Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cl	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Co	(Not assessed)		8×10^{-6}	3×10^{-4}	8×10^{-6}	3×10^{-4}	8×10^{-6}	3×10^{-4}
Ni	(Not assessed)		2×10^{-5}	1×10^{-4}	2×10^{-5}	1×10^{-4}	2×10^{-5}	1×10^{-4}
Se	2×10^{-6}	5×10^{-8}	3×10^{-5}	7×10^{-4}	3×10^{-5}	7×10^{-4}	2×10^{-5}	7×10^{-4}
Sr	4×10^{-4}	3×10^{-3}	1×10^{-4}	2×10^{-4}	1×10^{-4}	2×10^{-4}	9×10^{-5}	2×10^{-4}
Zr	2×10^{-8}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}	2×10^{-7}
Nb	5×10^{-5}	1×10^{-7}	5×10^{-2}	4×10^{-2}	5×10^{-2}	4×10^{-2}	4×10^{-2}	4×10^{-2}
Mo	(Not assessed)		4×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}	3×10^{-4}	3×10^{-4}
Tc	2×10^{-8}	8×10^{-8}	1×10^{-6}	9×10^{-7}	1×10^{-6}	9×10^{-7}	8×10^{-7}	7×10^{-7}
Pd	(Not assessed)		5×10^{-6}	2×10^{-3}	5×10^{-6}	2×10^{-3}	4×10^{-6}	2×10^{-3}
Sn	4×10^{-5}	3×10^{-6}	4×10^{-2}	4×10^{-2}	4×10^{-2}	4×10^{-2}	3×10^{-2}	3×10^{-2}
I	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Cs	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Pb	2×10^{-6}	4×10^{-6}	6×10^{-2}	5×10^{-2}	6×10^{-2}	5×10^{-2}	5×10^{-2}	5×10^{-2}
Ra	2×10^{-3}	1×10^{-2}	8×10^{-4}	9×10^{-4}	8×10^{-4}	9×10^{-4}	6×10^{-4}	8×10^{-4}
Ac	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble
Th	3×10^{-6}	5×10^{-5}	8×10^{-8}	8×10^{-8}	8×10^{-8}	8×10^{-8}	8×10^{-8}	8×10^{-8}
Pa	2×10^{-9}	2×10^{-8}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}	1×10^{-9}
U	5×10^{-5}	5×10^{-4}	2×10^{-5}	7×10^{-6}	2×10^{-5}	7×10^{-6}	1×10^{-5}	4×10^{-6}
Np	2×10^{-6}	4×10^{-5}	1×10^{-7}	1×10^{-7}	5×10^{-7}	5×10^{-7}	1×10^{-7}	1×10^{-7}
Pu	2×10^{-7}	9×10^{-5}	2×10^{-10}	2×10^{-10}	3×10^{-8}	3×10^{-8}	2×10^{-10}	2×10^{-10}
Am	2×10^{-6}	2×10^{-5}	5×10^{-10}	6×10^{-10}	7×10^{-10}	8×10^{-10}	5×10^{-10}	6×10^{-10}
Cm	2×10^{-6}	2×10^{-5}	5×10^{-10}	6×10^{-10}	7×10^{-10}	8×10^{-10}	5×10^{-10}	6×10^{-10}

Table 12 Effective diffusion coefficients of RNs in EBS materials (m^2/s) (Plutonic repository)

Components	Buffer				Infill
Analysis case	Base case		Variant case		Base case
Repository	HLW, TRU		HLW, TRU		TRU
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Average salinity
C (inorganic)	3×10^{-11}	3×10^{-11}	8×10^{-11}	8×10^{-11}	(Not assessed)
C (organic)	3×10^{-10}	3×10^{-10}	7×10^{-10}	7×10^{-10}	8×10^{-10}
Cl	5×10^{-11}	5×10^{-11}	2×10^{-10}	2×10^{-10}	8×10^{-10}
Co	5×10^{-8}	1×10^{-10}	2×10^{-7}	3×10^{-10}	8×10^{-10}
Ni	5×10^{-8}	1×10^{-10}	2×10^{-7}	3×10^{-10}	8×10^{-10}
Se	4×10^{-11}	5×10^{-11}	1×10^{-10}	1×10^{-10}	8×10^{-10}
Sr	4×10^{-8}	3×10^{-9}	2×10^{-7}	9×10^{-9}	8×10^{-10}
Zr	1×10^{-10}	1×10^{-10}	3×10^{-10}	3×10^{-10}	8×10^{-10}
Nb	1×10^{-10}	1×10^{-10}	3×10^{-10}	3×10^{-10}	8×10^{-10}
Mo	3×10^{-11}	3×10^{-11}	6×10^{-11}	6×10^{-11}	8×10^{-10}
Tc	1×10^{-10}	1×10^{-10}	3×10^{-10}	3×10^{-10}	8×10^{-10}
Pd	1×10^{-10}	1×10^{-10}	3×10^{-10}	3×10^{-10}	8×10^{-10}
Sn	1×10^{-10}	1×10^{-10}	3×10^{-10}	3×10^{-10}	8×10^{-10}
I	5×10^{-11}	5×10^{-11}	2×10^{-10}	2×10^{-10}	8×10^{-10}
Cs	8×10^{-9}	2×10^{-9}	2×10^{-8}	5×10^{-9}	8×10^{-10}
Pb	1×10^{-10}	1×10^{-9}	3×10^{-10}	3×10^{-9}	8×10^{-10}
Ra	5×10^{-8}	3×10^{-9}	2×10^{-7}	1×10^{-8}	8×10^{-10}
Ac	4×10^{-9}	1×10^{-9}	9×10^{-9}	3×10^{-9}	8×10^{-10}
Th	1×10^{-10}	1×10^{-10}	3×10^{-10}	3×10^{-10}	8×10^{-10}
Pa	5×10^{-8}	3×10^{-9}	2×10^{-7}	1×10^{-8}	8×10^{-10}
U	1×10^{-10}	1×10^{-10}	3×10^{-10}	3×10^{-10}	8×10^{-10}
Np	1×10^{-10}	1×10^{-10}	3×10^{-10}	3×10^{-10}	8×10^{-10}
Pu	4×10^{-9}	1×10^{-9}	9×10^{-9}	3×10^{-9}	8×10^{-10}
Am	4×10^{-9}	1×10^{-9}	9×10^{-9}	3×10^{-9}	8×10^{-10}
Cm	4×10^{-9}	1×10^{-9}	9×10^{-9}	3×10^{-9}	8×10^{-10}

Table 13 Effective diffusion coefficients of RNs in EBS materials (m^2/s) (Neogene repository)

Components	Buffer				Infill
Analysis case	Base case		Variant case		Base case
Repository	HLW, TRU		HLW, TRU		TRU
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Average salinity
C (inorganic)	2×10^{-11}	8×10^{-11}	6×10^{-11}	3×10^{-10}	(Not assessed)
C (organic)	2×10^{-10}	2×10^{-10}	5×10^{-10}	5×10^{-10}	6×10^{-10}
Cl	4×10^{-11}	5×10^{-11}	9×10^{-11}	8×10^{-11}	6×10^{-10}
Co	5×10^{-8}	5×10^{-10}	2×10^{-7}	2×10^{-9}	6×10^{-10}
Ni	5×10^{-8}	5×10^{-10}	2×10^{-7}	2×10^{-9}	6×10^{-10}
Se	3×10^{-11}	4×10^{-11}	8×10^{-11}	7×10^{-11}	6×10^{-10}
Sr	4×10^{-8}	4×10^{-10}	2×10^{-7}	2×10^{-9}	6×10^{-10}
Zr	8×10^{-11}	7×10^{-11}	3×10^{-10}	3×10^{-10}	6×10^{-10}
Nb	2×10^{-11}	7×10^{-11}	5×10^{-11}	3×10^{-10}	6×10^{-10}
Mo	2×10^{-11}	3×10^{-11}	5×10^{-11}	4×10^{-11}	6×10^{-10}
Tc	8×10^{-11}	7×10^{-11}	3×10^{-10}	3×10^{-10}	6×10^{-10}
Pd	8×10^{-11}	3×10^{-10}	3×10^{-10}	7×10^{-10}	6×10^{-10}
Sn	8×10^{-11}	7×10^{-11}	3×10^{-10}	3×10^{-10}	6×10^{-10}
I	4×10^{-11}	5×10^{-11}	9×10^{-11}	8×10^{-11}	6×10^{-10}
Cs	7×10^{-9}	7×10^{-10}	2×10^{-8}	2×10^{-9}	6×10^{-10}
Pb	8×10^{-11}	7×10^{-11}	3×10^{-10}	3×10^{-10}	6×10^{-10}
Ra	4×10^{-8}	4×10^{-10}	2×10^{-7}	2×10^{-9}	6×10^{-10}
Ac	3×10^{-9}	3×10^{-10}	7×10^{-9}	7×10^{-10}	6×10^{-10}
Th	8×10^{-11}	3×10^{-11}	3×10^{-10}	4×10^{-11}	6×10^{-10}
Pa	5×10^{-8}	7×10^{-10}	2×10^{-7}	2×10^{-9}	6×10^{-10}
U	8×10^{-11}	3×10^{-11}	3×10^{-10}	4×10^{-11}	6×10^{-10}
Np	8×10^{-11}	3×10^{-11}	3×10^{-10}	4×10^{-11}	6×10^{-10}
Pu	3×10^{-9}	3×10^{-10}	7×10^{-9}	7×10^{-10}	6×10^{-10}
Am	3×10^{-9}	3×10^{-10}	7×10^{-9}	7×10^{-10}	6×10^{-10}
Cm	3×10^{-9}	3×10^{-10}	7×10^{-9}	7×10^{-10}	6×10^{-10}

Table 14 Effective diffusion coefficients of RNs in EBS materials (m^2/s) (Pre-Neogene repository)

Components	Buffer				Infill
Analysis case	Base case		Variant case		Base case
Repository	HLW, TRU		HLW, TRU		TRU
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Average salinity
C (inorganic)	3×10^{-11}	2×10^{-10}	8×10^{-11}	4×10^{-10}	(Not assessed)
C (organic)	3×10^{-10}	2×10^{-10}	7×10^{-10}	7×10^{-10}	8×10^{-10}
Cl	5×10^{-11}	7×10^{-11}	2×10^{-10}	1×10^{-10}	8×10^{-10}
Co	6×10^{-8}	6×10^{-10}	2×10^{-7}	2×10^{-9}	8×10^{-10}
Ni	6×10^{-8}	6×10^{-10}	2×10^{-7}	2×10^{-9}	8×10^{-10}
Se	4×10^{-11}	6×10^{-11}	1×10^{-10}	9×10^{-11}	8×10^{-10}
Sr	5×10^{-8}	5×10^{-10}	2×10^{-7}	2×10^{-9}	8×10^{-10}
Zr	1×10^{-10}	9×10^{-11}	3×10^{-10}	3×10^{-10}	8×10^{-10}
Nb	1×10^{-10}	9×10^{-11}	3×10^{-10}	3×10^{-10}	8×10^{-10}
Mo	3×10^{-11}	4×10^{-11}	6×10^{-11}	5×10^{-11}	8×10^{-10}
Tc	1×10^{-10}	9×10^{-11}	3×10^{-10}	3×10^{-10}	8×10^{-10}
Pd	1×10^{-10}	5×10^{-10}	3×10^{-10}	9×10^{-10}	8×10^{-10}
Sn	1×10^{-10}	9×10^{-11}	3×10^{-10}	3×10^{-10}	8×10^{-10}
I	5×10^{-11}	7×10^{-11}	2×10^{-10}	1×10^{-10}	8×10^{-10}
Cs	9×10^{-9}	9×10^{-10}	2×10^{-8}	2×10^{-9}	8×10^{-10}
Pb	1×10^{-10}	5×10^{-10}	3×10^{-10}	9×10^{-10}	8×10^{-10}
Ra	6×10^{-8}	6×10^{-10}	2×10^{-7}	2×10^{-9}	8×10^{-10}
Ac	5×10^{-9}	5×10^{-10}	9×10^{-9}	9×10^{-10}	8×10^{-10}
Th	1×10^{-10}	4×10^{-11}	3×10^{-10}	5×10^{-11}	8×10^{-10}
Pa	6×10^{-8}	9×10^{-10}	2×10^{-7}	2×10^{-9}	8×10^{-10}
U	1×10^{-10}	4×10^{-11}	3×10^{-10}	5×10^{-11}	8×10^{-10}
Np	1×10^{-10}	4×10^{-11}	3×10^{-10}	5×10^{-11}	8×10^{-10}
Pu	5×10^{-9}	5×10^{-10}	9×10^{-9}	9×10^{-10}	8×10^{-10}
Am	5×10^{-9}	5×10^{-10}	9×10^{-9}	9×10^{-10}	8×10^{-10}
Cm	5×10^{-9}	5×10^{-10}	9×10^{-9}	9×10^{-10}	8×10^{-10}

Table 15 Sorption distribution coefficients for engineered barrier materials (m^3/kg) (Plutonic repository)

Components	Buffer				Infill			
Analysis case	Base case		Variant case		Base case			
Repository	HLW, TRU		HLW, TRU		Gr.1, 4L		Gr.3	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	0	0	0	0	(Not assessed)		(Not assessed)	
C (organic)	0	0	0	0	0	0	0	0
Cl	0	0	0	0	0	0	0	0
Co	3	3	7×10^{-1}	7×10^{-1}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Ni	3	3	7×10^{-1}	7×10^{-1}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Se	4×10^{-4}	4×10^{-4}	0	0	1×10^{-2}	1×10^{-2}	1×10^{-2}	1×10^{-2}
Sr	2×10^{-3}	2×10^{-3}	9×10^{-4}	9×10^{-4}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Zr	3	3	7×10^{-1}	7×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}
Nb	2×10^{-1}	2×10^{-1}	5×10^{-2}	5×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}
Mo	0	0	0	0	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Tc	5	5	1	1	1×10^{-1}	1×10^{-1}	2×10^{-5}	2×10^{-5}
Pd	5×10^{-2}	5×10^{-2}	1×10^{-2}	1×10^{-2}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Sn	3	3	7×10^{-1}	7×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}
I	0	0	0	0	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}
Cs	6×10^{-2}	6×10^{-2}	3×10^{-2}	3×10^{-2}	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}
Pb	4×10	4×10	1×10	1×10	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Ra	2×10^{-3}	2×10^{-3}	9×10^{-4}	9×10^{-4}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Ac	8×10^{-1}	8×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Th	8×10^{-1}	8×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Pa	2×10	2×10	8	8	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}
U	2×10^{-3}	2×10^{-3}	4×10^{-4}	4×10^{-4}	2×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}
Np	1	1	3×10^{-1}	3×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Pu	1×10	1×10	3	3	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Am	8×10^{-1}	8×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Cm	8×10^{-1}	8×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}

Table 16 Sorption distribution coefficients for engineered barrier materials (m^3/kg) (Neogene repository)

Components	Buffer				Infill			
Analysis case	Base case		Variant case		Base case			
Repository	HLW, TRU		HLW, TRU		Gr.1, 4L		Gr.3	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	0	0	0	0	(Not assessed)		(Not assessed)	
C (organic)	0	0	0	0	0	0	0	0
Cl	0	0	0	0	0	0	0	0
Co	3	3	7×10^{-1}	7×10^{-1}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Ni	3	3	7×10^{-1}	7×10^{-1}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Se	4×10^{-4}	4×10^{-4}	0	0	1×10^{-2}	1×10^{-2}	1×10^{-2}	1×10^{-2}
Sr	2×10^{-3}	6×10^{-3}	9×10^{-4}	5×10^{-4}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Zr	3	3	7×10^{-1}	7×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}
Nb	2×10^{-1}	2×10^{-1}	5×10^{-2}	5×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}
Mo	0	0	0	0	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Tc	5	5	1	1	1×10^{-1}	1×10^{-1}	2×10^{-5}	2×10^{-5}
Pd	5×10^{-2}	5×10^{-2}	1×10^{-2}	1×10^{-2}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Sn	3	3	7×10^{-1}	7×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}
I	0	0	0	0	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}
Cs	6×10^{-2}	4×10^{-2}	3×10^{-2}	7×10^{-3}	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}
Pb	4×10	4×10	1×10	1×10	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Ra	2×10^{-3}	2×10^{-2}	9×10^{-4}	4×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Ac	8×10^{-1}	8×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Th	8×10^{-1}	8×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Pa	2×10	2×10	8	8	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}
U	2×10^{-3}	2×10^{-3}	4×10^{-4}	4×10^{-4}	2×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}
Np	1	1	3×10^{-1}	3×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Pu	1×10	1×10	3	3	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Am	8×10^{-1}	8×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Cm	8×10^{-1}	8×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}

Table 17 Sorption distribution coefficients for engineered barrier materials (m^3/kg) (Pre-Neogene repository)

Components	Buffer				Infill			
Analysis case	Base case		Variant case		Base case			
Repository	HLW, TRU		HLW, TRU		Gr.1, 4L		Gr.3	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	0	0	0	0	(Not assessed)		(Not assessed)	
C (organic)	0	0	0	0	0	0	0	0
Cl	0	0	0	0	0	0	0	0
Co	3	3	7×10^{-1}	7×10^{-1}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Ni	3	3	7×10^{-1}	7×10^{-1}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Se	4×10^{-4}	4×10^{-4}	0	0	1×10^{-2}	1×10^{-2}	1×10^{-2}	1×10^{-2}
Sr	2×10^{-3}	6×10^{-3}	9×10^{-4}	5×10^{-4}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Zr	3	3	7×10^{-1}	7×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}
Nb	2×10^{-1}	2×10^{-1}	5×10^{-2}	5×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}
Mo	0	0	0	0	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Tc	5	5	1	1	1×10^{-1}	1×10^{-1}	2×10^{-5}	2×10^{-5}
Pd	5×10^{-2}	5×10^{-2}	1×10^{-2}	1×10^{-2}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Sn	3	3	7×10^{-1}	7×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}
I	0	0	0	0	1×10^{-4}	1×10^{-4}	1×10^{-4}	1×10^{-4}
Cs	6×10^{-2}	4×10^{-2}	3×10^{-2}	7×10^{-3}	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}
Pb	4×10	4×10	1×10	1×10	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Ra	2×10^{-3}	2×10^{-2}	9×10^{-4}	4×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Ac	8×10^{-1}	8×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Th	8×10^{-1}	8×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Pa	2×10	2×10	8	8	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}
U	2×10^{-3}	2×10^{-3}	4×10^{-4}	4×10^{-4}	2×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}
Np	1	1	3×10^{-1}	3×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Pu	1×10	1×10	3	3	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Am	8×10^{-1}	8×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}
Cm	8×10^{-1}	8×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}	2×10^{-1}

Table 18 Effective diffusion coefficients of RNs in host rock (m^2/s) (Plutonic repository)

Analysis case	Base case	Variant case
Repository	HLW, TRU	HLW, TRU
All RNs	9×10^{-13}	5×10^{-14}

Table 19 Effective diffusion coefficients of RNs in host rock (m^2/s) (Neogene repository)

Analysis case	Base case				Variant case			
Repository	HLW, Gr.1, 2, 4		Gr.3		HLW, Gr.1, 2, 4		Gr.3	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	1×10^{-11}	1×10^{-11}	(Not assessed)		2×10^{-12}	2×10^{-12}	(Not assessed)	
C (organic)	6×10^{-11}	6×10^{-11}	1×10^{-11}	1×10^{-11}	3×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
Cl	1×10^{-11}	1×10^{-11}	1×10^{-11}	1×10^{-11}	2×10^{-12}	2×10^{-12}	2×10^{-12}	2×10^{-12}
Co	6×10^{-11}	1×10^{-10}	1×10^{-11}	1×10^{-11}	3×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
Ni	6×10^{-11}	1×10^{-10}	1×10^{-11}	1×10^{-11}	3×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
Se	1×10^{-11}	1×10^{-11}	1×10^{-11}	1×10^{-11}	2×10^{-12}	2×10^{-12}	2×10^{-12}	2×10^{-12}
Sr	1×10^{-10}	1×10^{-10}	1×10^{-11}	1×10^{-11}	3×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
Zr	6×10^{-11}	1×10^{-11}	1×10^{-11}	1×10^{-11}	3×10^{-12}	2×10^{-12}	2×10^{-12}	2×10^{-12}
Nb	1×10^{-11}	1×10^{-11}	1×10^{-11}	1×10^{-11}	2×10^{-12}	2×10^{-12}	2×10^{-12}	2×10^{-12}
Mo	1×10^{-11}	1×10^{-11}	1×10^{-11}	1×10^{-11}	2×10^{-12}	2×10^{-12}	2×10^{-12}	2×10^{-12}
Tc	6×10^{-11}	6×10^{-11}	1×10^{-11}	1×10^{-11}	3×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
Pd	6×10^{-11}	1×10^{-10}	1×10^{-11}	1×10^{-11}	3×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
Sn	1×10^{-11}	6×10^{-11}	1×10^{-11}	1×10^{-11}	2×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
I	1×10^{-11}	1×10^{-11}	1×10^{-11}	1×10^{-11}	2×10^{-12}	2×10^{-12}	2×10^{-12}	2×10^{-12}
Cs	1×10^{-10}	1×10^{-10}	1×10^{-11}	1×10^{-11}	3×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
Pb	6×10^{-11}	6×10^{-11}	1×10^{-11}	1×10^{-11}	3×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
Ra	1×10^{-10}	1×10^{-10}	1×10^{-11}	1×10^{-11}	3×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
Ac	1×10^{-11}	1×10^{-10}	1×10^{-11}	1×10^{-11}	2×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
Th	1×10^{-11}	1×10^{-11}	1×10^{-11}	1×10^{-11}	2×10^{-12}	2×10^{-12}	2×10^{-12}	2×10^{-12}
Pa	1×10^{-11}	1×10^{-11}	1×10^{-11}	1×10^{-11}	2×10^{-12}	2×10^{-12}	2×10^{-12}	2×10^{-12}
U	1×10^{-11}	1×10^{-11}	1×10^{-11}	1×10^{-11}	2×10^{-12}	2×10^{-12}	2×10^{-12}	2×10^{-12}
Np	1×10^{-11}	1×10^{-11}	1×10^{-11}	1×10^{-11}	2×10^{-12}	2×10^{-12}	2×10^{-12}	2×10^{-12}
Pu	1×10^{-11}	1×10^{-10}	1×10^{-11}	1×10^{-11}	2×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
Am	1×10^{-11}	1×10^{-10}	1×10^{-11}	1×10^{-11}	2×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}
Cm	1×10^{-11}	1×10^{-10}	1×10^{-11}	1×10^{-11}	2×10^{-12}	3×10^{-12}	2×10^{-12}	2×10^{-12}

Table 20 Effective diffusion coefficients of RNs in host rock (m^2/s) (Pre-Neogene repository)

Analysis case	Base case				Variant case			
Repository	HLW, Gr.1, 2, 4		Gr.3		HLW, Gr.1, 2, 4		Gr.3	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	3×10^{-13}	3×10^{-13}	(Not assessed)		4×10^{-14}	4×10^{-14}	(Not assessed)	
C (organic)	3×10^{-12}	3×10^{-12}	3×10^{-13}	3×10^{-13}	9×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
Cl	3×10^{-13}	3×10^{-13}	3×10^{-13}	3×10^{-13}	4×10^{-14}	4×10^{-14}	4×10^{-14}	4×10^{-14}
Co	3×10^{-12}	2×10^{-12}	3×10^{-13}	3×10^{-13}	9×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
Ni	3×10^{-12}	2×10^{-12}	3×10^{-13}	3×10^{-13}	9×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
Se	3×10^{-13}	3×10^{-13}	3×10^{-13}	3×10^{-13}	4×10^{-14}	4×10^{-14}	4×10^{-14}	4×10^{-14}
Sr	2×10^{-12}	2×10^{-12}	3×10^{-13}	3×10^{-13}	9×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
Zr	3×10^{-12}	3×10^{-13}	3×10^{-13}	3×10^{-13}	9×10^{-14}	4×10^{-14}	4×10^{-14}	4×10^{-14}
Nb	3×10^{-13}	3×10^{-13}	3×10^{-13}	3×10^{-13}	4×10^{-14}	4×10^{-14}	4×10^{-14}	4×10^{-14}
Mo	3×10^{-13}	3×10^{-13}	3×10^{-13}	3×10^{-13}	4×10^{-14}	4×10^{-14}	4×10^{-14}	4×10^{-14}
Tc	3×10^{-12}	3×10^{-12}	3×10^{-13}	3×10^{-13}	9×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
Pd	3×10^{-12}	2×10^{-12}	3×10^{-13}	3×10^{-13}	9×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
Sn	3×10^{-13}	3×10^{-12}	3×10^{-13}	3×10^{-13}	4×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
I	3×10^{-13}	3×10^{-13}	3×10^{-13}	3×10^{-13}	4×10^{-14}	4×10^{-14}	4×10^{-14}	4×10^{-14}
Cs	2×10^{-12}	2×10^{-12}	3×10^{-13}	3×10^{-13}	9×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
Pb	3×10^{-12}	3×10^{-12}	3×10^{-13}	3×10^{-13}	9×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
Ra	2×10^{-12}	2×10^{-12}	3×10^{-13}	3×10^{-13}	9×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
Ac	2×10^{-12}	2×10^{-12}	3×10^{-13}	3×10^{-13}	9×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
Th	3×10^{-13}	3×10^{-13}	3×10^{-13}	3×10^{-13}	4×10^{-14}	4×10^{-14}	4×10^{-14}	4×10^{-14}
Pa	3×10^{-13}	3×10^{-13}	3×10^{-13}	3×10^{-13}	4×10^{-14}	4×10^{-14}	4×10^{-14}	4×10^{-14}
U	3×10^{-13}	3×10^{-13}	3×10^{-13}	3×10^{-13}	4×10^{-14}	4×10^{-14}	4×10^{-14}	4×10^{-14}
Np	3×10^{-13}	3×10^{-13}	3×10^{-13}	3×10^{-13}	4×10^{-14}	4×10^{-14}	4×10^{-14}	4×10^{-14}
Pu	3×10^{-13}	2×10^{-12}	3×10^{-13}	3×10^{-13}	4×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
Am	2×10^{-12}	2×10^{-12}	3×10^{-13}	3×10^{-13}	9×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}
Cm	2×10^{-12}	2×10^{-12}	3×10^{-13}	3×10^{-13}	9×10^{-14}	9×10^{-14}	4×10^{-14}	4×10^{-14}

Table 21 Distribution coefficients for sorption on host rock (m^3/kg) (Plutonic repository) (1/2)

Analysis case	Base case					
Repository	HLW, Gr.1, 2, 4		Gr.3 (< 1,000 y after repository closure)		Gr.3 (> 1,000 y after repository closure	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	0	0	(Not assessed)		(Not assessed)	
C (organic)	0	0	0	0	0	0
Cl	0	0	0	0	0	0
Co	1×10^{-1}	1×10^{-1}	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-5}
Ni	1×10^{-1}	1×10^{-1}	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-5}
Se	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Sr	8×10^{-3}	8×10^{-3}	8×10^{-6}	8×10^{-6}	8×10^{-5}	8×10^{-5}
Zr	8×10^{-1}	8×10^{-1}	8×10^{-1}	8×10^{-1}	8×10^{-1}	8×10^{-1}
Nb	4×10^{-1}	4×10^{-1}	4×10^{-1}	4×10^{-1}	4×10^{-1}	4×10^{-1}
Mo	0	0	0	0	0	0
Tc	8	8	8	8	8	8
Pd	6×10^{-1}	6×10^{-1}	6×10^{-3}	6×10^{-3}	6×10^{-3}	6×10^{-3}
Sn	1×10	1×10	1×10	1×10	1×10	1×10
I	0	0	0	0	0	0
Cs	4×10^{-2}	4×10^{-2}	4×10^{-5}	4×10^{-5}	4×10^{-4}	4×10^{-4}
Pb	1	1	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Ra	1×10^{-1}	1×10^{-1}	1×10^{-4}	1×10^{-4}	1×10^{-3}	1×10^{-3}
Ac	1	1	1	1	1	1
Th	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}
Pa	2	2	2	2	2	2
U	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}
Np	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}
Pu	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}
Am	1	1	1	1	1	1
Cm	1	1	1	1	1	1

Table 21 Distribution coefficients for sorption on host rock (m^3/kg) (Plutonic repository) (2/2)

Analysis case	Variant case					
Repository	HLW, Gr.1, 2, 4		Gr.3 (< 1,000 y after repository closure)		Gr.3 (> 1,000 y after repository closure)	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	0	0	(Not assessed)		(Not assessed)	
C (organic)	0	0	0	0	0	0
Cl	0	0	0	0	0	0
Co	6×10^{-3}	6×10^{-3}	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-5}
Ni	6×10^{-3}	6×10^{-3}	1×10^{-5}	1×10^{-5}	1×10^{-5}	1×10^{-5}
Se	3×10^{-4}	3×10^{-4}	3×10^{-4}	3×10^{-4}	3×10^{-4}	3×10^{-4}
Sr	5×10^{-4}	5×10^{-4}	8×10^{-6}	8×10^{-6}	8×10^{-5}	8×10^{-5}
Zr	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}
Nb	5×10^{-2}	5×10^{-2}	5×10^{-2}	5×10^{-2}	5×10^{-2}	5×10^{-2}
Mo	0	0	0	0	0	0
Tc	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}	3×10^{-1}
Pd	4×10^{-2}	4×10^{-2}	6×10^{-3}	6×10^{-3}	6×10^{-3}	6×10^{-3}
Sn	5×10^{-1}	5×10^{-1}	5×10^{-1}	5×10^{-1}	5×10^{-1}	5×10^{-1}
I	0	0	0	0	0	0
Cs	1×10^{-3}	1×10^{-3}	4×10^{-5}	4×10^{-5}	4×10^{-4}	4×10^{-4}
Pb	2×10^{-1}	2×10^{-1}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Ra	1×10^{-2}	1×10^{-2}	1×10^{-4}	1×10^{-4}	1×10^{-3}	1×10^{-3}
Ac	7×10^{-2}	7×10^{-2}	7×10^{-2}	7×10^{-2}	7×10^{-2}	7×10^{-2}
Th	8×10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}
Pa	9×10^{-3}	9×10^{-3}	9×10^{-3}	9×10^{-3}	9×10^{-3}	9×10^{-3}
U	8×10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}
Np	8×10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}
Pu	8×10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}	8×10^{-3}
Am	7×10^{-2}	7×10^{-2}	7×10^{-2}	7×10^{-2}	7×10^{-2}	7×10^{-2}
Cm	7×10^{-2}	7×10^{-2}	7×10^{-2}	7×10^{-2}	7×10^{-2}	7×10^{-2}

Table 22 Distribution coefficients for sorption on host rock (m^3/kg) (Neogene repository) (1/2)

Analysis case	Base case					
Repository	HLW, Gr.1, 2, 4		Gr.3 (< 1,000 y)		Gr.3 (> 1,000 y)	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	0	0	(Not assessed)		(Not assessed)	
C (organic)	0	0	0	0	0	0
Cl	0	0	0	0	0	0
Co	3	5×10^{-1}	3×10^{-4}	5×10^{-5}	3×10^{-4}	5×10^{-5}
Ni	3	5×10^{-1}	3×10^{-4}	5×10^{-5}	3×10^{-4}	5×10^{-5}
Se	4×10^{-2}	5×10^{-2}	4×10^{-2}	5×10^{-2}	4×10^{-2}	5×10^{-2}
Sr	2×10^{-1}	7×10^{-2}	2×10^{-4}	7×10^{-5}	2×10^{-3}	7×10^{-4}
Zr	2	0	2	0	2	0
Nb	6	6	6	6	6	6
Mo	0	0	0	0	0	0
Tc	1×10^{-2}	0	1×10^{-2}	0	1×10^{-2}	0
Pd	1	3	1×10^{-2}	3×10^{-2}	1×10^{-2}	3×10^{-2}
Sn	1×10^{2}	1×10^{2}	1×10^{2}	1×10^{2}	1×10^{2}	1×10^{2}
I	0	0	0	0	0	0
Cs	1	1×10^{-1}	1×10^{-3}	1×10^{-4}	1×10^{-2}	1×10^{-3}
Pb	2	0	2×10^{-3}	0	2×10^{-3}	0
Ra	3×10^{-1}	3×10^{-2}	3×10^{-4}	3×10^{-5}	3×10^{-3}	3×10^{-4}
Ac	2×10^{2}	2×10	2×10^{2}	2×10	2×10^{2}	2×10
Th	3×10	5	3×10	5	3×10	5
Pa	2	2	2	2	2	2
U	6	2×10^{-6}	6	2×10^{-6}	6	2×10^{-6}
Np	3×10	5	3×10	5	3×10	5
Pu	3×10	5	3×10	5	3×10	5
Am	2×10^{2}	2×10	2×10^{2}	2×10	2×10^{2}	2×10
Cm	2×10^{2}	2×10	2×10^{2}	2×10	2×10^{2}	2×10

Table 22 Distribution coefficients for sorption on host rock (m^3/kg) (Neogene repository) (2/2)

Analysis case	Variant case					
Repository	HLW, Gr.1, 2, 4		Gr.3 (< 1,000 y)		Gr.3 (> 1,000 y)	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	0	0	(Not assessed)		(Not assessed)	
C (organic)	0	0	0	0	0	0
Cl	0	0	0	0	0	0
Co	8×10^{-1}	4×10^{-1}	3×10^{-4}	5×10^{-5}	3×10^{-4}	5×10^{-5}
Ni	8×10^{-1}	4×10^{-1}	3×10^{-4}	5×10^{-5}	3×10^{-4}	5×10^{-5}
Se	2×10^{-2}	5×10^{-2}	2×10^{-2}	5×10^{-2}	2×10^{-2}	5×10^{-2}
Sr	1×10^{-2}	2×10^{-2}	2×10^{-4}	7×10^{-5}	2×10^{-3}	7×10^{-4}
Zr	2	0	2	0	2	0
Nb	6	6	6	6	6	6
Mo	0	0	0	0	0	0
Tc	1×10^{-2}	0	1×10^{-2}	0	1×10^{-2}	0
Pd	7×10^{-2}	7×10^{-1}	1×10^{-2}	3×10^{-2}	1×10^{-2}	3×10^{-2}
Sn	6×10	6×10	6×10	6×10	6×10	6×10
I	0	0	0	0	0	0
Cs	4×10^{-2}	5×10^{-3}	1×10^{-3}	1×10^{-4}	1×10^{-2}	1×10^{-3}
Pb	1	0	2×10^{-3}	0	2×10^{-3}	0
Ra	1×10^{-1}	1×10^{-2}	3×10^{-4}	3×10^{-5}	3×10^{-3}	3×10^{-4}
Ac	1×10^{2}	1×10	1×10^{2}	1×10	1×10^{2}	1×10
Th	2×10	5	2×10	5	2×10	5
Pa	2	2	2	2	2	2
U	4	8×10^{-8}	4	8×10^{-8}	4	8×10^{-8}
Np	2×10	5	2×10	5	2×10	5
Pu	2×10	5	2×10	5	2×10	5
Am	1×10^{2}	1×10	1×10^{2}	1×10	1×10^{2}	1×10
Cm	1×10^{2}	1×10	1×10^{2}	1×10	1×10^{2}	1×10

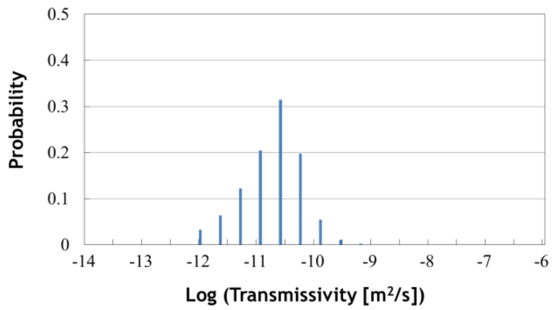
Table 23 Distribution coefficients for sorption on host rock (m^3/kg) (Pre-Neogene repository) (1/2)

Analysis case	Base case					
Repository	HLW, Gr.1, 2, 4		Gr.3 (< 1,000 y)		Gr.3 (> 1,000 y)	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	0	0	(Not assessed)		(Not assessed)	
C (organic)	0	0	0	0	0	0
Cl	0	0	0	0	0	0
Co	3	5×10^{-1}	3×10^{-4}	5×10^{-5}	3×10^{-4}	5×10^{-5}
Ni	3	5×10^{-1}	3×10^{-4}	5×10^{-5}	3×10^{-4}	5×10^{-5}
Se	4×10^{-2}	5×10^{-2}	4×10^{-2}	5×10^{-2}	4×10^{-2}	5×10^{-2}
Sr	2×10^{-1}	7×10^{-2}	2×10^{-4}	7×10^{-5}	2×10^{-3}	7×10^{-4}
Zr	2	0	2	0	2	0
Nb	6	6	6	6	6	6
Mo	0	0	0	0	0	0
Tc	1×10^{-2}	0	1×10^{-2}	0	1×10^{-2}	0
Pd	1	3	1×10^{-2}	3×10^{-2}	1×10^{-2}	3×10^{-2}
Sn	1×10^{2}	1×10^{2}	1×10^{2}	1×10^{2}	1×10^{2}	1×10^{2}
I	0	0	0	0	0	0
Cs	1	1×10^{-1}	1×10^{-3}	1×10^{-4}	1×10^{-2}	1×10^{-3}
Pb	2	0	2×10^{-3}	0	2×10^{-3}	0
Ra	3×10^{-1}	3×10^{-2}	3×10^{-4}	3×10^{-5}	3×10^{-3}	3×10^{-4}
Ac	2×10^{2}	2×10	2×10^{2}	2×10	2×10^{2}	2×10
Th	3×10	5	3×10	5	3×10	5
Pa	2	2	2	2	2	2
U	1×10	2×10^{-6}	1×10	2×10^{-6}	1×10	2×10^{-6}
Np	3×10	5	3×10	5	3×10	5
Pu	3×10	5	3×10	5	3×10	5
Am	2×10^{2}	2×10	2×10^{2}	2×10	2×10^{2}	2×10
Cm	2×10^{2}	2×10	2×10^{2}	2×10	2×10^{2}	2×10

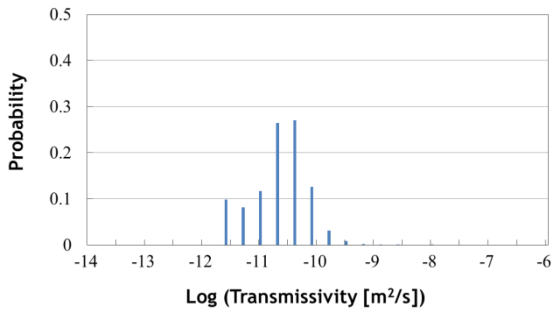
Table 23 Distribution coefficients for sorption on host rock (m^3/kg) (Pre-Neogene repository) (2/2)

Analysis case	Variant case					
Repository	HLW, Gr.1, 2, 4		Gr.3 (< 1,000 y)		Gr.3 (> 1,000 y)	
Groundwater	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
C (inorganic)	0	0	(Not assessed)		(Not assessed)	
C (organic)	0	0	0	0	0	0
Cl	0	0	0	0	0	0
Co	8×10^{-1}	4×10^{-1}	3×10^{-4}	5×10^{-5}	3×10^{-4}	5×10^{-5}
Ni	8×10^{-1}	4×10^{-1}	3×10^{-4}	5×10^{-5}	3×10^{-4}	5×10^{-5}
Se	2×10^{-2}	5×10^{-2}	2×10^{-2}	5×10^{-2}	2×10^{-2}	5×10^{-2}
Sr	1×10^{-2}	2×10^{-2}	2×10^{-4}	7×10^{-5}	2×10^{-4}	7×10^{-4}
Zr	2	0	2	0	2	0
Nb	6	6	6	6	6	6
Mo	0	0	0	0	0	0
Tc	1×10^{-2}	0	1×10^{-2}	0	1×10^{-2}	0
Pd	7×10^{-2}	7×10^{-1}	1×10^{-2}	3×10^{-2}	1×10^{-2}	3×10^{-2}
Sn	6×10	6×10	6×10	6×10	6×10	6×10
I	0	0	0	0	0	0
Cs	4×10^{-2}	5×10^{-3}	1×10^{-3}	1×10^{-4}	1×10^{-2}	1×10^{-3}
Pb	1	0	2×10^{-3}	0	2×10^{-3}	0
Ra	1×10^{-1}	1×10^{-2}	3×10^{-4}	3×10^{-5}	3×10^{-3}	3×10^{-4}
Ac	1×10^{2}	1×10	1×10^{2}	1×10	1×10^{2}	1×10
Th	2×10	5	2×10	5	2×10	5
Pa	2	2	2	2	2	2
U	8	8×10^{-8}	8	8×10^{-8}	8	8×10^{-8}
Np	2×10	5	2×10	5	2×10	5
Pu	2×10	5	2×10	5	2×10	5
Am	1×10^{2}	1×10	1×10^{2}	1×10	1×10^{2}	1×10
Cm	1×10^{2}	1×10	1×10^{2}	1×10	1×10^{2}	1×10

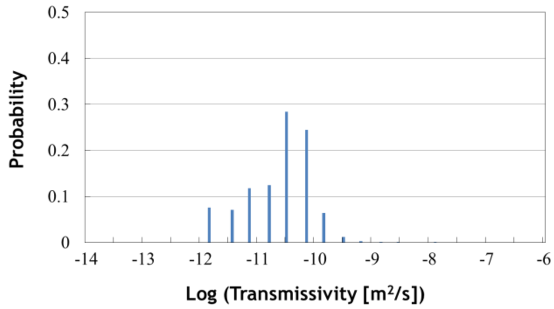
HLW repository (H12V)



TRU repository (Gr.1, Gr.2, Gr.4HD, Gr.4HH)

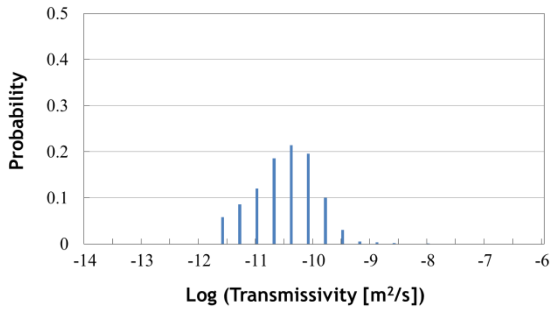


HLW repository (PEM)



TRU repository (Gr.3, Gr.4LD, Gr.4LC)

Leaching of RNs starts immediately after repository closure



TRU repository (Gr.3, Gr.4LD, Gr.4LC)

Leaching of RNs begins 300 y after repository closure

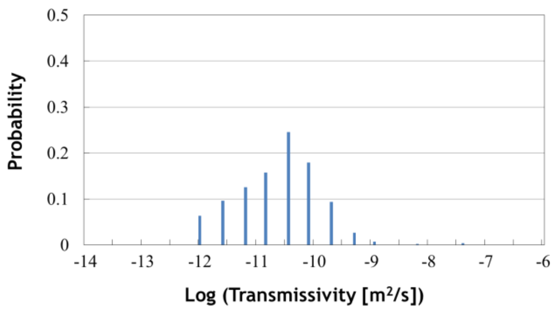


Figure 1 Transmissivity distribution of near field scale channels for the Base case (Plutonic)

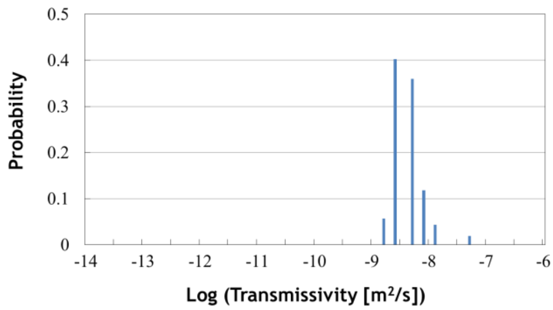
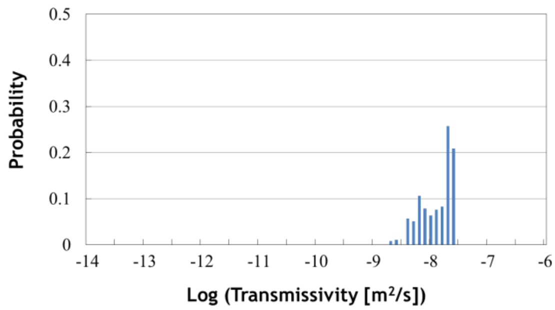
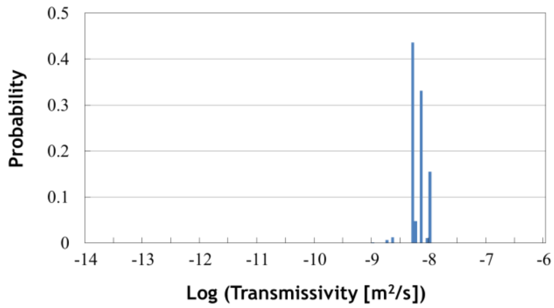
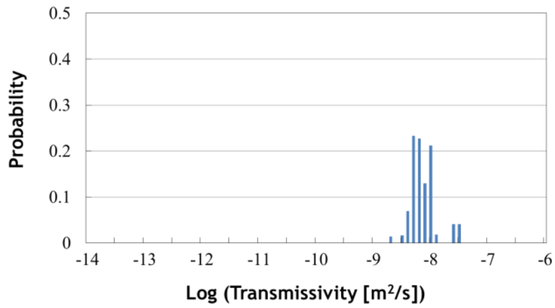
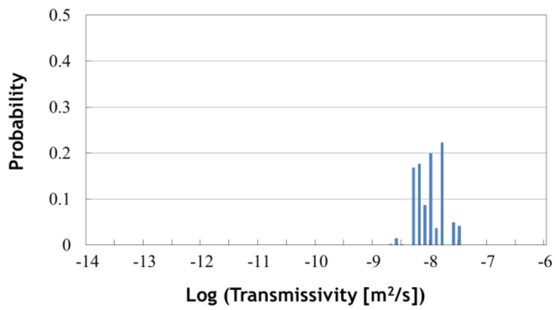
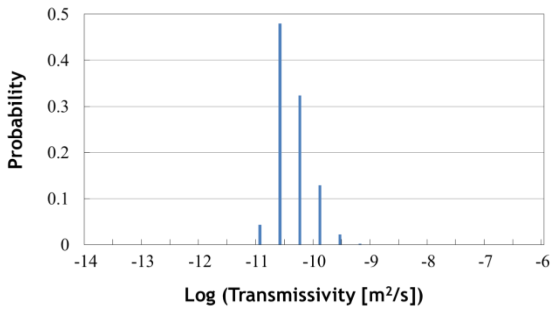
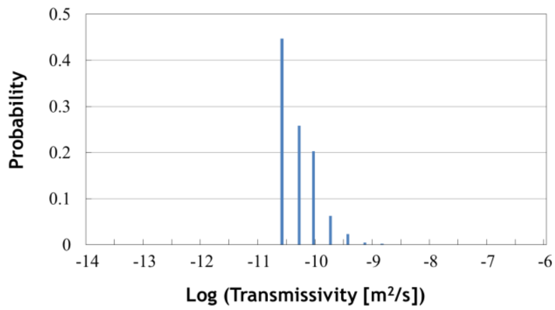
HLW repository (H12V)	TRU repository (Gr.1, Gr.2, Gr.4HD, Gr.4HH)
	
HLW repository (PEM)	TRU repository (Gr.3, Gr.4LD, Gr.4LC) Leaching of RNs starts immediately after repository closure
	
	TRU repository (Gr.3, Gr.4LD, Gr.4LC) Leaching of RNs begins 300 y after repository closure
	

Figure 2 Transmissivity distribution of near field scale channels for the Base case (Neogene sediments)

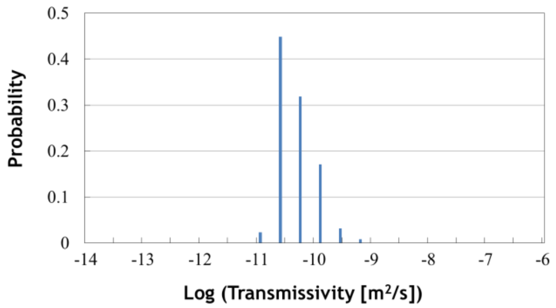
HLW repository (H12V)



TRU repository (Gr.1, Gr.2, Gr.4HD, Gr.4HH)

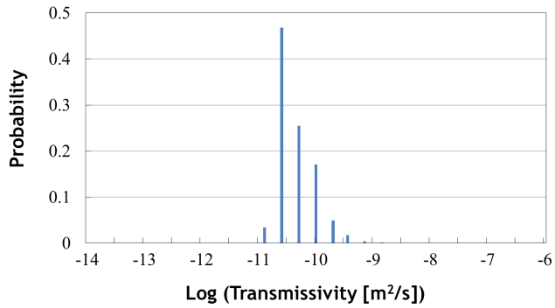


HLW repository (PEM)



TRU repository (Gr.3, Gr.4LD, Gr.4LC)

Leaching of RNs starts immediately after repository closure



TRU repository (Gr.3, Gr.4LD, Gr.4LC)

Leaching of RNs begins 300 y after repository closure

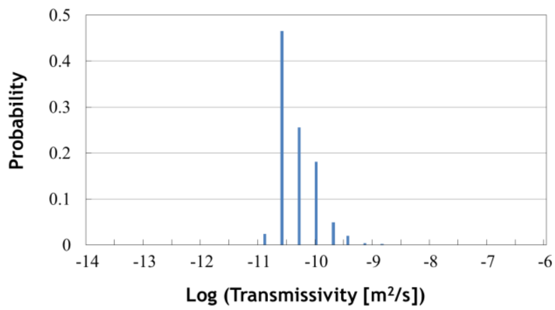
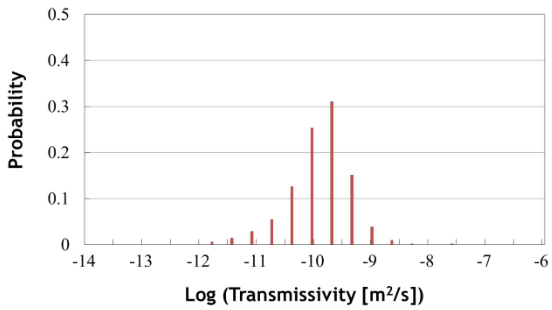
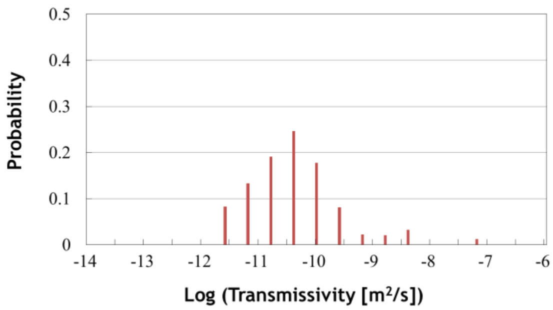


Figure 3 Transmissivity distribution of near field scale channels for the Base case (Pre-Neogene sediments)

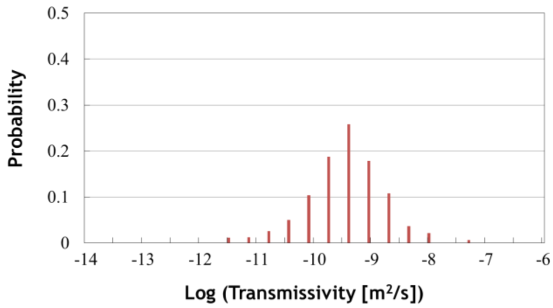
HLW repository (H12V)



TRU repository (Gr.1, Gr.2, Gr.4HD, Gr.4HH)

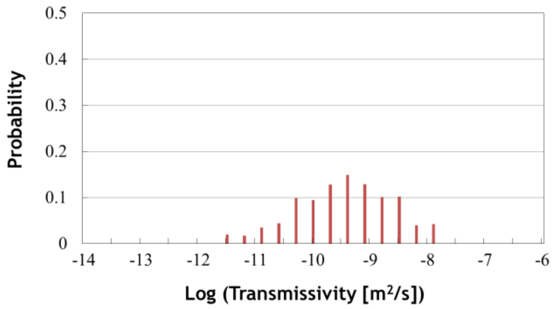


HLW repository (PEM)



TRU repository (Gr.3, Gr.4LD, Gr.4LC)

Leaching of RNs starts immediately after repository closure



TRU repository (Gr.3, Gr.4LD, Gr.4LC)

Leaching of RNs begins 300 y after repository closure

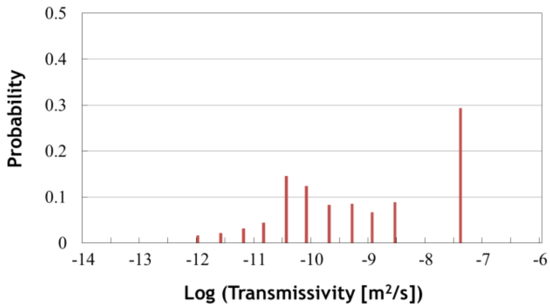
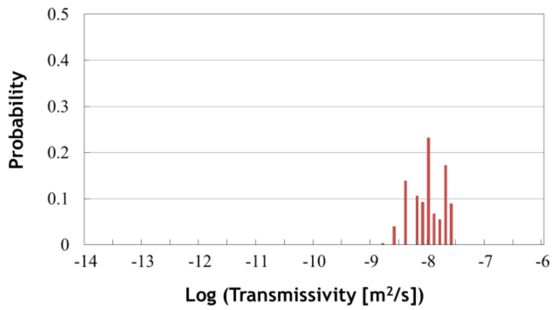
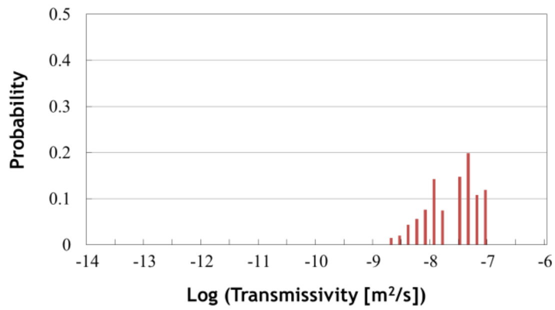


Figure 4 Variant case – near field scale host rock fracture connectivity Transmissivity distribution of channels (Plutonic)

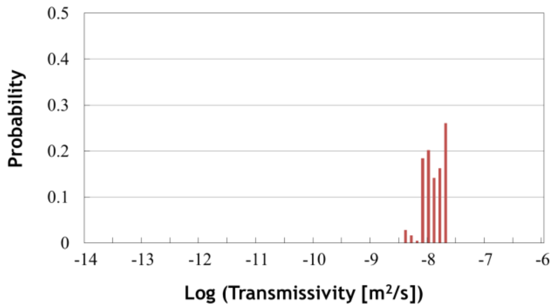
HLW repository (H12V)



TRU repository (Gr.1, Gr.2, Gr.4HD, Gr.4HH)

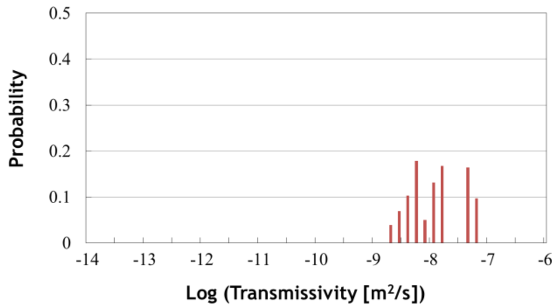


HLW repository (PEM)



TRU repository (Gr.3, Gr.4LD, Gr.4LC)

Leaching of RNs starts immediately after repository closure



TRU repository (Gr.3, Gr.4LD, Gr.4LC)

Leaching of RNs begins 300 y after repository closure

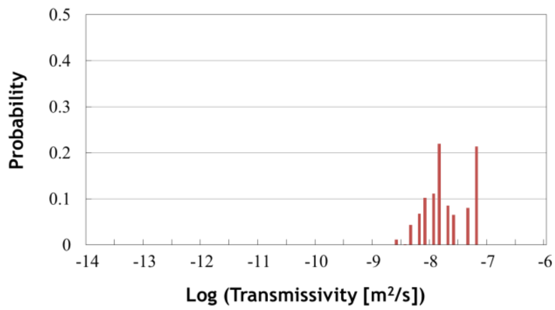


Figure 5 Variant case – near field scale host rock fracture connectivity Transmissivity distribution of channels (Neogene sediments)

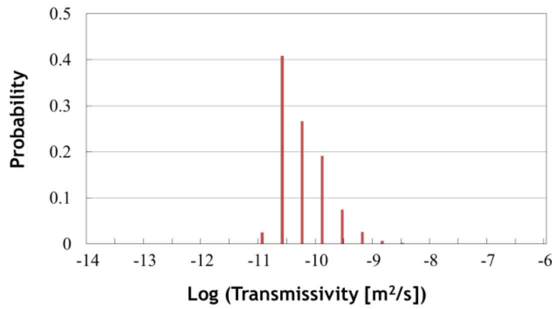
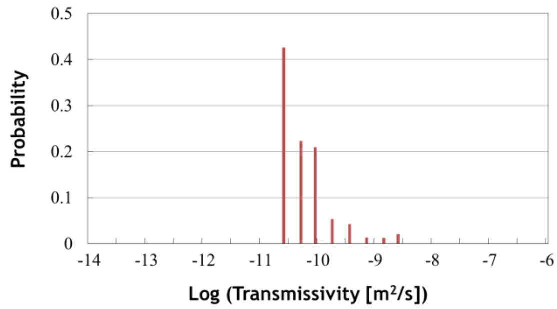
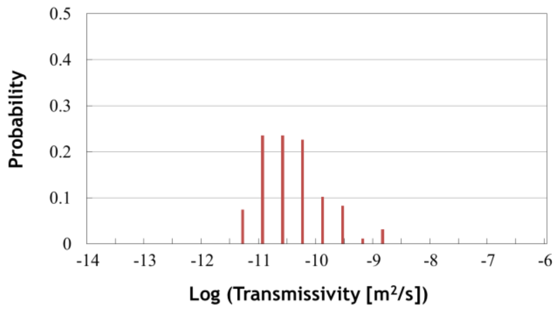
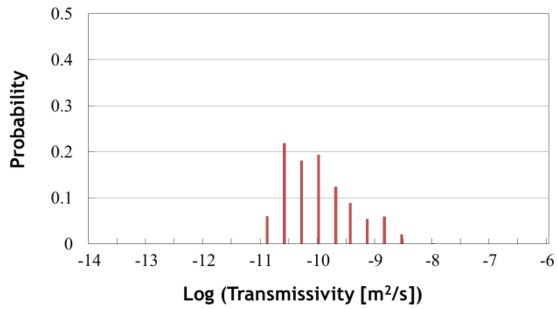
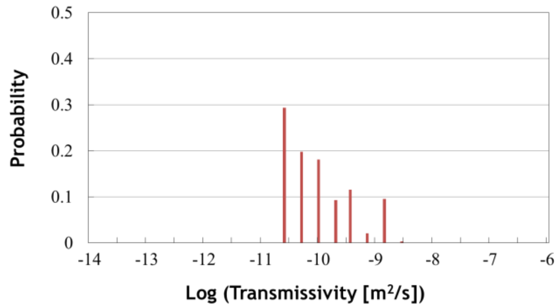
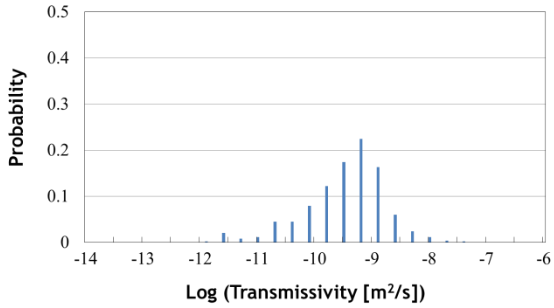
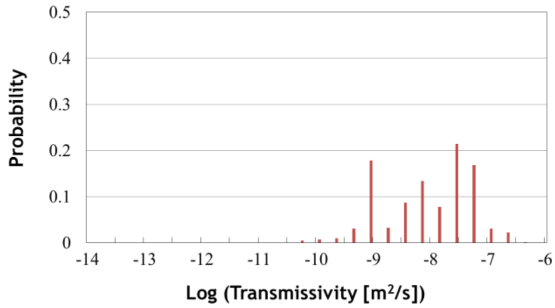
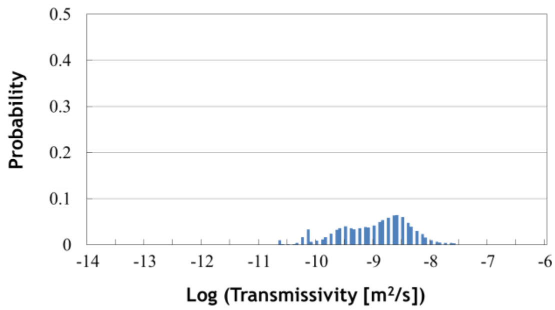
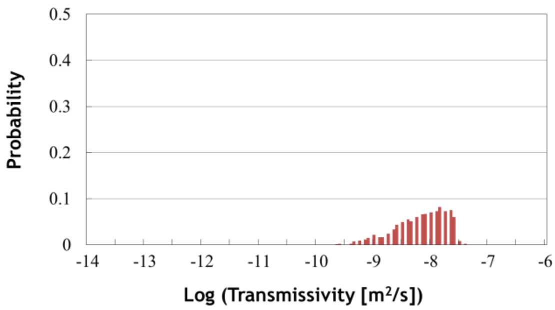
HLW repository (H12V)	TRU repository (Gr.1, Gr.2, Gr.4HD, Gr.4HH)
	
HLW repository (PEM)	TRU repository (Gr.3, Gr.4LD, Gr.4LC) Leaching of RNs starts immediately after repository closure
	
	TRU repository (Gr.3, Gr.4LD, Gr.4LC) Leaching of RNs begins 300 y after repository closure
	

Figure 6 Variant case – near field scale host rock fracture connectivity Transmissivity distribution of channels (Pre-Neogene sediments)

Plutonic

Base case	Variant case
	

Neogene sediments

Base case	Variant case
	

Pre-Neogene sediments

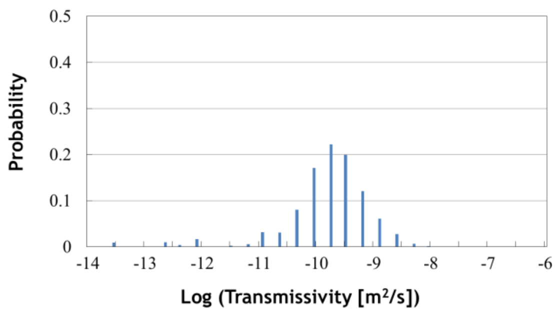
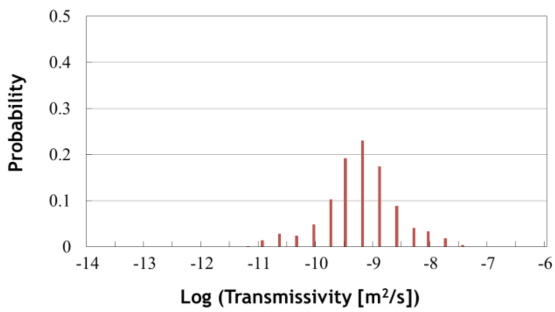
Base case	Variant case
	

Figure 7 Base and Variant cases - host rock fracture connectivity
Distribution of transmissivities in repository-scale channels

7 SAFETY CASE SYNTHESIS

7.1 Objectives of this chapter

As noted in Chapter 1, this report presents a safety case that does not target a specific site, but uses the latest scientific knowledge and technological developments to assess the feasibility and safety of geological disposal in representative Japanese geological environments. The aim is therefore to illustrate, as summarised in this chapter, a safety case framework and the associated technical basis that can be applied in the future to any identified site. A related intention is that this chapter should function as a standalone description of the Safety Case for readers who have not read the other chapters. For this reason, Chapter 7 summarises some of the key findings in earlier chapters and adds the additional elements needed for a safety case.

The basic approach involved is discussed in Chapter 2 and applied in a stepwise manner through Chapters 3-6.

- In addition to showing a method for identifying geological environments suitable for hosting a repository, representative rock types were selected that are widely distributed in Japan in order to illustrate how nationwide geological information can be integrated into representative site descriptive models (SDMs) (Chapter 3).
- A method for repository design based on the required safety functions was illustrated, which specifically shows how specifications of a repository can be tailored to these SDMs (Chapter 4).
- Such tailored designs are assessed in terms of safety, both before and after closure (Chapter 5, Chapter 6).
- Through these studies, research and development efforts were identified that will provide required further safety case improvement in the future (each chapter).

In this chapter, based on this input, multiple lines of evidence are developed to build a safety case [1] [2] that is appropriate to the current pre-siting stage of our programme. Therefore, for the goals and boundary conditions set for this report (Chapter 2), arguments include consideration of the following points:

(1) The established approach for building a repository with the required safety features in relevant Japanese geological environments (the basic components of the safety case as shown in Figure 1.4-2) that is consistent with the current scientific and technological state-of-the-art. This provides the knowledge base required in order to proceed with siting after the Literature Survey (LS) commences in volunteer communities.

(2) The established safety assessment methodology, tools and data that form a sound basis for evaluation of the safety of geological disposal concepts tailored to appropriate geological environments.

(3) The efforts made to increase confidence in the safety case in terms of supporting arguments in which:

- The quality of established procedures leading from the creation of SDMs to the design of the repository and the associated safety assessment is shown to be assured by an appropriately structured, logical methodology.

- Appropriate procedures to deal with the range of uncertainties that need to be considered are clarified, together with measures to manage these in the future.
- Developments in the technical knowledge base since the H12 [3] and TRU-2 [4] reports are analysed.

(4) To ensure that lessons learnt from the different stages in the programme will be addressed, and thereby further improve confidence, creation of a safety case template that can incorporate the results of step-by-step site surveys and technological development in updates that are produced as required at programme milestones.

The points are considered further in the following sections.

7.2 Integration of arguments in a safety case

As described in Chapter 2, the basic idea of implementing a deep geological repository with the required safety functions includes:

(1) Avoiding natural perturbing phenomena that may have a significant impact on the repository by selecting a geological environment that maintains favourable characteristics for a long period of time.

(2) For such a geological environment, assurance of radiological safety, general occupational safety and minimal impacts on the surrounding environment during construction, operation, and after closure. Design of the repository thus includes engineering measures so that the safety functions relating both to the operational and post-closure phases of the multi-barrier system last for a sufficient period of time.

(3) For all credible future evolution scenarios, assessed potential radiological impacts are assured to lie below targets appropriate to their likelihood of occurrence, providing confidence that the required safety functions are robust, even in the light of inherent uncertainties.

In the following, the three fundamental technologies that form the basis for the evaluation required to provide assurance of safety are summarised, based on the material already presented in Chapters 3-6:

- Technology for characterising suitable geological environments to support site selection.
- Technology for designing and implementing a repository with the required safety functions for relevant geological environments.
- Technology to evaluate the safety of such a repository.

7.2.1 Summary of the basis for safety evaluation

(1) Basis for selection of suitable geological environments

In contrast to siting approaches in countries involving nomination of favoured sites, the Japanese approach of calling for volunteers, supported by a map that identifies scientifically favourable locations, means that the site selection process will involve an initial LS in applicant regions that may contain various possible host rocks. To accommodate such a range of potential geological settings, assessment techniques are required that can be tailored to sites as necessary during the different investigation phases. This requires:

i. Clarification of the general requirements and criteria for determining site eligibility in a stepwise site selection process.

ii. Systematic development of characterisation technology needed to acquire geological information necessary for judging site eligibility in light of specific requirements/criteria, together with that for integrating such information into a site descriptive model (SDM).

iii. Checks of the applicability of such technologies on the basis of evolving understanding of specific sites.

Regarding these, the relevant material from Chapter 3 is summarised in the following.

(i) Requirements/criteria for site selection and their application in stepwise surveys

The Geological Disposal Technology WG re-examined the requirements and criteria for selection of sites suitable for geological disposal [5], based on the scientific knowledge accumulated since the H12 report. In addition to post-closure safety of the repository and the practicality and safety of construction, operation and transportation were considered. Based on this, areas with scientific features relevant to geological disposal were presented in the Nationwide Map [6].

In this report, technical considerations associated with statutory terminology requirements and criteria to be considered during stepwise site selection were summarised in Section 2.1.3 (1). Furthermore, Section 3.1 discussed the requirements and criteria for determining the eligibility of such sites, with emphasis on safety during construction, operation and closure of the repository and assurance of isolation and containment safety functions for specific geological environments. In particular, areas at risk from perturbing natural phenomena, now or in the future, will be excluded on the basis of the planned stepwise investigations. For any potentially eligible site, the selection process takes into account expected long-term evolution of the site geological environment, for which a properly selected EBS can provide sufficient safety functions even accounting for such evolution processes.

As established in the Basic Policy on Final Disposal, the Nuclear Regulatory Authority will specify factors to be considered during the selection of Preliminary Investigation Areas (PIAs), following Literature Survey (LS) of volunteer sites. These factors should then be taken into account when formulating siting requirements/criteria. The factors specified in the future for stepwise selecting Detailed Investigation Areas (DIAs) and, finally, the repository site, should also be reflected at these project milestones.

(ii) Development of required investigation/assessment technology

The required technology for characterising the geological environment and assessing the potential impacts of natural perturbing phenomena during stepwise site investigations was summarised in Section 3.2, with emphasis on technological developments since the H12 report. At the Preliminary Investigation (PI) stage, non-invasive surface mapping and geophysical surveys lead to a programme of characterisation boreholes, using approaches and technology established in areas such as natural resource exploration and underground construction (summarised in Supporting Report 3-11). A combination of these individual technologies can provide the geological knowledge base necessary for demonstrating that perturbing natural phenomena are avoided and to serve for the design and safety assessment of the repository. This knowledge is based on an approach developed and demonstrated at the JAEA underground research laboratories (URLs, see Figure 3.2-3 in Section 3.2.2), and is incorporated in a work flow specified for the LS and PI stages. Additionally, a planning manual [8] and documents related to quality management (see Supporting Report 3-12) have been prepared to facilitate these investigations. The applicability of the concepts and technology for the PI stage has also been established, and practical experience gained, particularly in collaborative NUMO/CRIEPI studies of borehole investigation technology [9].

With a particular focus on understanding evolution of the geological environment and the potential impacts of natural perturbing phenomena, NUMO is reviewing the state-of-the-art technologies systematically to assure best available technology is applied at LS and PI stages for specific sites. Also R&D for developing technologies for Detailed Investigation (DI) is ongoing in JAEA URLs, aiming to provide further input for selecting best technology for that stage (for example, [10] [11]).

Although siting is intended to avoid the risk of natural perturbations that could cause significant impacts on the repository (for example, volcanism), for particular assessment timescales beyond 100 ky, extending to ≈ 1 My, any assurance inevitably involves greater uncertainty due to the limits of current knowledge. Thus, NUMO has investigated a probabilistic method to quantitatively assess risks (ITM-TOPAZ technique) [12], which forms a basis to increase confidence in the associated safety assessment.

(iii) Information integration into a SDM

JAEA 's URL research [13] [14] iteratively evaluates the relationship between the type, quality and quantity of information and the degree of understanding of the geological environment as site investigation progresses. By feeding back such understanding into the planning of the next investigation step, this approach gradually reduces uncertainty in understanding the spatially heterogeneous characteristics of the geological environment. It has also been demonstrated that the SDM developed by integrating such investigation results can be used to effectively support design and construction of underground facilities.

In Section 3.3, based on geological information gathered on a nationwide scale, plus that from URLs, the distribution of different rocks at relevant depths was assessed. By focusing on key attributes required for a repository (e.g. practicality of safe construction, appropriate barrier properties in terms of RN containment), three representative host rocks with different characteristics were selected: plutonic rocks, Neogene sediments, and Pre-Neogene sediments. In order to develop SDMs, in addition to representative geological settings, the length, density, and orientation of faults and fractures as well as other structural features, together with their associated hydrogeological characteristics, were set based on observations throughout Japan. SDMs at regional scale (tens of km × tens of km), repository scale (5 km × 5 km), and panel scale (800 m × 800 m) were developed, with the level of detail increasing as dimensions decrease (see Figure 7.2-1). For each host rock, appropriate thermal and mechanical properties were established along with model groundwater chemistries and small-scale descriptions of groundwater flow paths.

As emphasis is on the deep environment, the descriptions of topography and surface/shallow geological features are illustrative only, without specified quantitative information. In any case, these characteristics are extremely site specific and could vary greatly even for a specified host rock. Thus, the characteristics of, and evolution scenarios for, the surface environment are not explicitly discussed in this report. The evolution of the geological environment of the host rock is also not discussed explicitly, as it is assumed to be stable for long a time and its evolution might depend on that of the surface environment. In coming assessments these aspects will be given more attention.

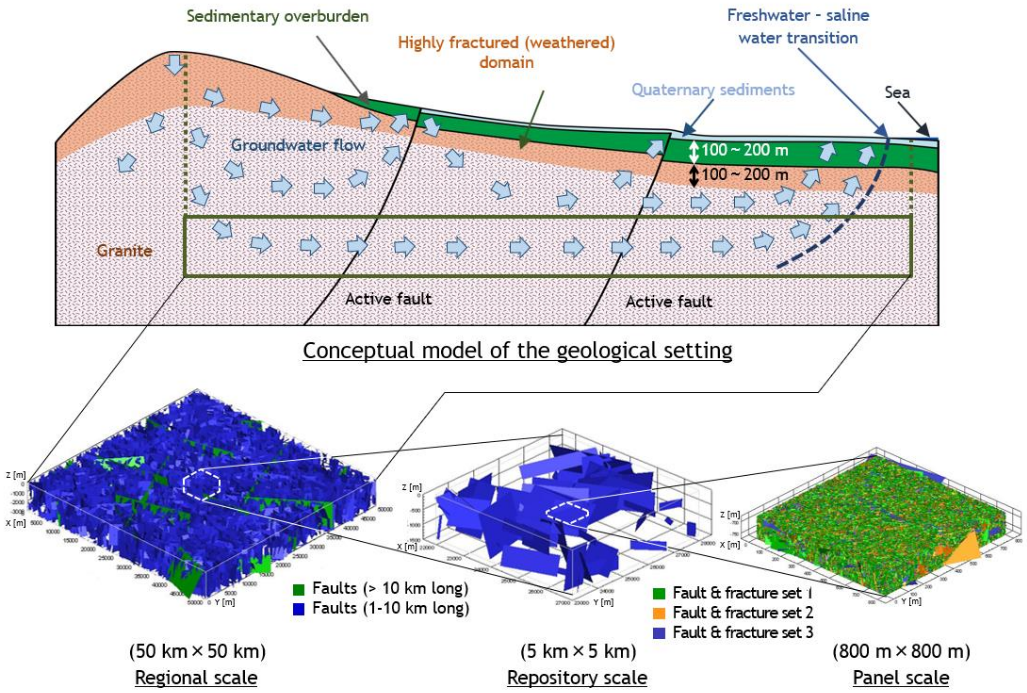


Figure 7.2-1 SDM illustration at different scales (example of plutonic rocks) (Integrating Figures 3.3-3, 3.3-9, 3.3-28, and 3.3-44). Note that the description of topography is illustrative only. In the future, when SDMs are developed for actual sites, local scale variations in topography that may impact groundwater flow will be captured.

Nevertheless, the surface characteristics are accepted to be key attributes of sites, with quantitative information being provided by applying the investigation technology described in (ii) above.

As described in Section 2.2.5, the present report assumes that underground facilities will be located at sufficient depth within a stable geological setting (which is likely to be much deeper that than the legally required minimum depth 300 m for placement of the repository), so that significant impacts from uplift and erosion would not occur over relevant timescales. However, as described in Section 3.2.2, due to the limited information that can be obtained during the LS stage, temporal evolution of the SDM is represented at a conceptual level only. A more quantitative SDM, capturing evolution with time (a “4D” SDM), will be developed only during the PI stage, although NUMO is already assessing the information and technology required to develop such models.

(iv) Current status and future needs

As described in (i) to (iii) above, NUMO will utilise BAT (term expanded as either “best available techniques” or “best available technology”) to ensure any site selected meets the requirements and criteria for determining its eligibility. The availability of required technology has been established or it is currently under development. The applicability of such technologies for NUMO's specific needs is confirmed by demonstration tests at research sites and in URLs. Thus, it can be said that the technical basis for investigations after LS has been established.

As discussed in Section 3.5.2, in order to better assure the suitability of specific geological settings to host a repository, NUMO will continue a focused programme of R&D, including:

- Improving the understanding of natural perturbations that may affect the safety functions of a repository (volcanic/igneous activity, volcanic hydrothermal/deep fluid movement, earthquake/fault activity, uplift/erosion). This will include better determination of probability of occurrence, together with associated impacts, which will allow improved representation of perturbation scenarios and more complete capture of included uncertainties, to form the basis for focused design counter-measures to reduce impacts and more realistic assessment of safety margins.
- Improving investigation technology with a particular focus on the requirements to develop and refine the SDMs and to also cover the site evolution (4D SDM) during the PI and DI stages, leading up to selection of a site for repository implementation. This will include characterisation of the features of sites that determine the release of radionuclides (RNs) from the engineered barrier system (EBS) and their transport to a well-defined geosphere-biosphere interface (GBI). Again, output will be focused by the requirements of evolving repository designs and associated safety assessments.

Investigation plans and technology used will be tailored to the conditions of specific sites (geology, geography/topography, socio-political constraints, etc.). As previously noted, this will allow focused determination of the potential significance of uplift and erosion (e.g. Supporting Report 6-10) and allow models to be developed that assess consequences for different repository designs, taking into account the timescale for safety assessment.

(2) Basis for repository design and implementation

To construct a repository that meets the required pre- and post-closure safety functions, key considerations include:

- The characteristics and quantity of waste to be disposed of, leading to design requirements set to assure safety functions expected for each component of the repository, including engineered barriers and associated surface and underground facilities. The methodology allows tailoring the specifications of each component of the repository, in order to flexibly satisfy the design requirements for constraints set by siting environments (see Section 2.1.2 (4)).
- Utilisation of engineering technology to construct, operate, and close such a repository that has been demonstrated to be applicable or that can be reasonably be expected based on future technological development.

For the HLW repository, as in the H12 report, NUMO will incorporate a system of multiple engineered barriers, with robust design of performance and applicability to a wide range of stable geological environments. Thus, the design requirements for vitrified waste, overpacks, and buffer materials as engineered barriers and for supporting underground infrastructure have been identified. These are specified for each of the representative geological formations defined in the H12 report. Furthermore, through demonstration of production of overpacks and construction tests using buffer materials, it was shown that implementation can be carried out based on H12 report technology or that considered to be feasible in the near future.

For TRU waste, as in the TRU-2 report, the design of engineered barriers and underground facilities considers the characteristics of the four groups of such waste. These designs again lead to specifications for each geological formations considered. Also here, engineering tests support that the required technology for implementation is available, or is reasonably expected to be so in the near future.

Extending the basis established in the H12 and TRU-2 reports by taking into account the updated scientific and engineering knowledge base, Chapter 4 developed repository designs and assessed the required engineering technology, as summarised in the following.

(i) Repository design method

The design requirements for the repository considered in the H12 report focused predominantly on post-closure safety and engineering feasibility. Since H12, NUMO has introduced a comprehensive set of design requirements for individual components of the repository to meet design factors including: post-closure safety, operational safety, engineering practicality, retrievability, environmental impact and socio-economic aspects. By applying these requirements to corresponding components, detailed specifications are derived (materials, shape, dimensions, etc.). However, in this study, factors that are considered to be very site-specific, such as environmental impact and socio-economic aspects, are not considered in the design process, but will be as the siting programme proceeds.

As a starting point for developing repository concepts, those presented in the H12 and TRU-2 reports were re-assessed in the light of recent technology development. From the design requirements identified for individual design factors of each component of the HLW and TRU waste repositories, basic specifications that meet the design requirements are developed. In order to introduce more flexibility, variants of the disposal concept and associated technology for EBS implementation are considered. This will form a basis for future optimisation of the design and tailoring of concepts to the siting environment.

(ii) Reference repository designs

Designs of repositories for HLW and TRU waste are developed for the three reference SDMs assuming that these facilities will be co-located at a single site.

(a) Setting the disposal depth

A key parameter for the design of underground facilities is the implementation depth. This will be set on a site-specific basis, depending on the distribution of suitable host rock(s), subject to the fundamental constraint set by law that this should be 300 m or deeper. A balance has to be found between rock stability, practicality of drainage and ventilation during construction, which are generally more challenging at greater depths, and post-closure safety, which might be expected to improve with depth (especially with regard to future uplift and erosion). As previously noted (and discussed in Section 2.2.5), constraints set by uplift and erosion are not assessed prior to site-specific analyses. Pragmatically, therefore, a reference depth can be set as the greatest depth for which design can ensure reasonable stability of underground openings (tunnels, vaults) during construction and operation, while available equipment can provide required services, such as ventilation and drainage.

For the stronger plutonic rocks and Pre-Neogene sediments, the limiting practical constraint on depth is the construction safety requirement to keep temperatures in the tunnels below 37 °C by realistic ventilation equipment, leading to setting 1,000 m as the installation depth. For the weaker Neogene sediments, the requirement for cavity stability leads to setting the installation depth as 500 m. However, it should be noted that these depths are only indicative and are based on preliminary simplifying assumptions. As the designs are developed here on the deep side of the range of acceptable depths, this will indicate flexibility in tailoring to the depths of suitable formations at actual sites.

(b) EBS design

For the HLW repository, the specifications of the overpack and buffer derived in the H12 report [3] are taken over as they meet all the design requirements for the three SDMs. In this process, however, current knowledge indicates an overpack lifetime of more than 10 ky, far beyond the design requirement to prevent groundwater contacting the HLW for 1 ky (see Section 4.4.1). To assess constraints set by practicality of emplacement, an H12 in-hole option (H12V) is compared to a horizontal, in tunnel option with a prefabricated EBS module (PEM). For TRU waste, the TRU-2 waste package [4] (in the present report called waste package A) was reassessed along with a variant waste package that includes a lid and improved robustness against dropping (referred to as waste package B), and which facilitates operations by allowing lifting by a crane. The assessment shows that both options satisfy the design requirements for each waste group (see Section 4.4.2).

The designed EBS is set within a layout specified for each SDM (discussed further in (c) below), for example, as illustrated for the PEM and TRU waste in plutonic rock in Figure 4.4-18 and Figure 4.4-25 respectively, which are integrated in Figure 7.2-2.

The EBS design specifications meet current design requirements with sufficient margins for all three representative rocks, despite inherent uncertainties at the present time. These provide a sound basis for assessing operational and post-closure safety (described in Chapters 5 and 6). However, from a post closure perspective, not all aspects have been fully assessed, as already indicated in previous chapters. It is also important to recognise that these designs may be over-conservative and are certainly not optimised (see Section 7.2.1 (3)), which is an issue that will be considered when developing an EBS tailored to the geological environment and other boundary conditions for specific sites.

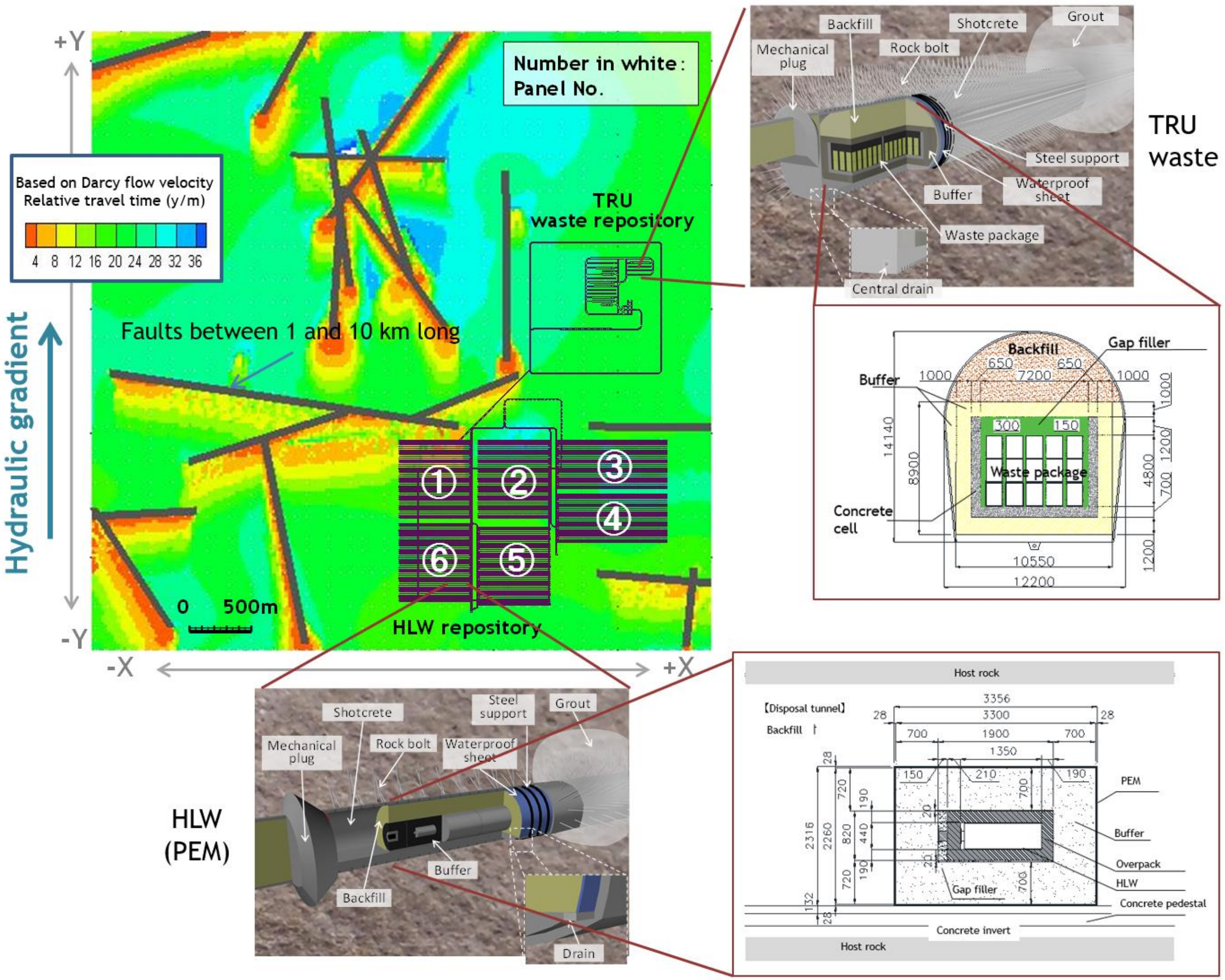


Figure 7.2-2 Example of EBS design and underground facility layout (Example of plutonic rocks, PEM dead-end emplacement tunnel)

(c) Underground facility design

For underground facilities, geological structures and hydrogeological conditions were considered in order to determine the shape and placement of tunnels and disposal panels in order to meet the design requirements (Section 4.5.4). In particular, concerns about potential water inflow during construction and/or operation and preferential paths for transport of any released RNs led to definition of layout determining features (LDFs), such as larger fault zones, that should be avoided during design. Together with orientation of the hydraulic gradient, such LDFs are the main constraints on disposal panel layout in plutonic rock, taking into account also inherent uncertainty in their specified locations – taken to be approximately 1% of the large fault length which is more than 1 km - Section 3.1.3 (1). For the sedimentary rocks, fold structures and permeability variations due to different lithologies present require additional considerations during development of layouts. Further, for the weaker Neogene sediments, tunnel orientation in relation to the ambient stress field has also to be taken into account.

On a smaller scale, emplacement determining features (EDFs) that result in localised water inflow need to be considered, as these impact the ability to excavate tunnels and disposal holes and assure that the EBS can be emplaced to required quality levels. For the defined distribution of such features in each SDM, the percentage of disposal holes or tunnels that can be used is quantified and, if required, the area of disposal panels increased.

By taking into account LDFs and EDFs, required design assessments can be conducted to ensure constructability and repository containment functions. For example, the size and distribution of faults, fractures and other features in which advective flow occurs is a particularly important characteristic in terms of ensuring the repository containment function. Design requirements are formulated and the design is adapted to such features and characteristics. Such adaption can also be further developed during future layout optimisation.

Additional issues to be considered when defining the layout of disposal panels involve the practicality of construction and operation, leading to specification and placement of access /connecting tunnels and shafts, ventilation shafts, effective work flow lines for transporting waste and material to/from construction zones, and ventilation/drainage routes in the tunnels. The procedure for assessing such issues focuses on worker safety (e.g., provision of multiple escape routes, counter-measures against accidents, etc) and work efficiency (especially given the relatively high reference emplacement rate for HLW). As an example, the resulting layouts for HLW PEMs and TRU waste in plutonic rocks are also shown in Figure 7.2-2.

Together with the EBS design, the layout is taken into account during the assessment of post-closure safety for the three different SDMs, as described in Chapter 6. This demonstration of requirements-driven design provides a foundation for tailoring layout to evolving SDMs produced during stepwise site investigations. In the future, however, feedback from post-closure assessment of RN migration will allow this to be directly considered along with operational safety and work efficiency in an optimisation process. For this, it is important to have a more realistic assessment of post-closure safety, as considered further in Section 7.2.1 (3).

(d) Design of surface facilities

For “active” surface facilities handling waste, the concepts and requirements already established for related nuclear facilities that handle, inspect, and package HLW and TRU waste can be applied to ensure radiation protection during operations. The resulting designs thus ensure radiation protection of both the general public and workers (see Section 4.6.2). For surface facilities (see Section 4.2.3 (4)) that do not handle radioactive material, conventional design approaches can be applied. The transportation of waste from interim storage elsewhere to the surface facility can utilise extensive experience in both land and marine transportation in Japan and other countries, including that of spent fuel and HLW. In particular, the specifications for transport containers and ships that return waste after overseas reprocessing are considered applicable to geological disposal operations (Section 4.6.1 (1)).

The approach illustrated in this report allows design of surface facilities that satisfy the required safety functions for the waste reception, inspection, and encapsulation processes that are most important from a radiation safety perspective. After sites are identified, NUMO will proceed with more detailed design of both surface facilities and transportation infrastructure, based on local environmental conditions. By constructing the surface facility directly above the disposal footprint, access tunnels can be shortened, which is advantageous in terms of safety, environmental protection, work efficiency, economics, etc. However, depending on site-specific constraints, spatial separation may be required in terms of optimisation, along with associated tailoring of concepts during stepwise characterisation to assure stakeholder acceptance, ease of construction of the underground facility and safety both before and after closure.

(iii) Technology required for repository construction, operation and closure

Basic research and development since the H12 report has led to improvements in technology related to practicality and quality assurance of fabrication of EBS components and their emplacement underground (see Section 4.4.3). For example, welding overpacks with a thickness of 19 cm and non-destructive detection of welding defects as small as 2 ~ 3 mm has been demonstrated [14][15]. For current overpack specifications, the analysis shows that, for a wide range of conditions, the safety function of suppressing contact between groundwater and HLW for at least 1 ky is greatly exceeded on the basis of well-established fabrication technology.

In addition, manufacture of full-scale buffer blocks with the required density for the H12V concept has been demonstrated [16], along with a vacuum suction technology allowing such blocks be gripped and placed in the disposal holes by remote control (on the basis of both domestic and overseas verification tests [17] [18]). PEM manufacture and transport is under development, with initial full-scale technology demonstrations ongoing [19]. As the PEM concept is similar to the horizontal Swedish KBS-3H option, demonstration tests of this method conducted at the Äspö URL are directly relevant [20]. For TRU waste, full-scale demonstration tests have included the construction of surrounding buffer and the filling of gaps between waste packages [21] [22]. These technological developments, for practical application under realistic deep underground conditions, provide confidence in the EBS construction techniques assumed in the illustrative designs (see Section 4.4.3).

In terms of general construction of underground facilities, the technology proven in existing facilities, such as the construction of underground power plants, can be applied. In addition, with regard to the tunnel backfill and plug construction technology required for repository closure, full-scale equipment development and demonstration tests in URLs are already underway in Japan and overseas (see Section 4.5.7). For the construction and operation of active surface facilities, technology that has been proven in existing nuclear facilities can be applied.

When considering ease of retrieval, it is necessary to prevent this function from adversely affecting operational or post-closure safety, e.g., due to delaying closure of the repository or parts of it containing waste. For example, to assure that ventilation air does not impact the corrosion resistance of the overpack, and in order to reduce erosion of buffer, disposal tunnels should be closed as soon as possible after waste is emplaced. Even after backfilling and emplacement of a mechanical plug, retrieval was shown to be technically feasible (see Section 4.7.1). In particular, development of a method of removing buffer around the H12V overpack with salt water is ongoing [23]. Such a technique can also be applied to the PEM backfill, which is considered to be easier to retrieve. Thus, at least before final closure, retrieval is considered to be sufficiently well demonstrated (see Section 4.7.2).

After sites are identified, technology will be refined, in line with evolution of the repository design and associated construction, operation and closure plan, based on information obtained from stepwise characterisation. This will combine demonstrations of engineering technology required with practical aspects of ensuring reliability and meeting quality levels to ensure designed safety functions during full scale implementation.

(iv) Current status and future needs

As shown above, based on information provided by the three SDMs, repositories can be designed that meet a range of requirements to realise expected safety functions and can be implemented based on existing technology. Nevertheless, the technology required to construct, operate and close such repositories will be continually re-assessed, based on progress in other relevant civil engineering areas, with the aim of assurance that application to geological disposal remains state-of-the-art and can be tailored to the evolving understanding of requirements for specific sites.

Depending on regulatory or socio-political requirements impacting the disposal plan, NUMO will move forward with more concrete designs incorporating optimisation, considering both operational and post-closure safety. For example, alternative materials and EBS designs can be assessed with the aim of improving engineering practicality, operational efficiency, flexibility to tailor to site conditions, socio-economic aspects, etc. This will require improved assessment technology for designs and construction/operation plans, such as better quantifying long-term behaviour of engineered barriers, assessing impacts of water inflow during tunnel excavation and responding to feedback from safety assessment.

Specifically, for the technology of waste retrieval, NUMO will further promote demonstration tests to confirm its feasibility. More generally, NUMO will continue to utilise the outcome from JAEA URLs and also plans increased participation in technology development and demonstration in international URLs, covering aspects of repository construction, EBS emplacement, monitoring and closure to required quality levels.

(3) Basis for safety assessment

The repository concepts developed for the representative SDMs, together with defined processes for construction, operation and closure, form the basis for safety assessment, with a current focus of radiological impacts both before and post-closure. At the present time, in the absence of specific national regulations for geological disposal, guidelines from international organisations and safety regulations in other countries are used to provide the technical foundation for a safety assessment based on the latest scientific knowledge. In terms of the period before the repository is closed, it is also necessary to ensure general occupational safety for workers based on safety measures and safety management applied in similar industries, in accordance with the Industrial Safety and Health Act. However, such safety is not considered in the present report.

Section 2.4 described the internationally agreed methodology for assessing radiological consequences[24] [25], which is adopted in this report. Safety assessment includes the following tasks:

- Repository features, events and processes (FEPs) impacting safety functions are systematically evaluated to establish a comprehensive set of scenarios.
- Quantitative analysis of such scenarios to determine possible radiological effects of the repository pre- and post-closure.
- Assessment of whether these radiological effects meet the given safety criteria and targets.

This safety assessment is based on that used for the H12 and TRU-2 reports, updated to reflect advances resulting in R&D since then. Chapter 5 presented the assessment of operational safety, whilst Chapter 6 covered post-closure safety.

(i) Operational safety

For safety assessment covering operation of the repository, regulatory standards and safety assessment methods for other nuclear facilities can be referred to. Radiation protection of workers and the surrounding public is assured by the design of equipment and procedures for handling radioactive material, incorporation of sufficient shielding and a comprehensive radiation monitoring system. Safety assessment calculates radiation exposure for normal operations and also for perturbed operational scenarios that are in line with the defence in depth principle, associated with all waste handling operations. Such assessment should confirm that the required level of safety can be ensured based on regulatory standards or identify aspects of the design of the repository that need to be reviewed. This also provides guidance for implementing appropriate radiation control and monitoring measures.

As noted in Chapter 5, with reference to IAEA safety guidelines [26] and new regulatory standards for nuclear facilities in Japan (promulgated after the Fukushima Daiichi Nuclear Power Plant accident), both planned operations at the repository (normal operations), and impacts of perturbing events (abnormal operations) are evaluated in this report. Under normal operating conditions, radioactive waste stores and handling equipment prevents leakage of radioactivity, with maintenance of a negative pressure preventing external loss of any surface contamination that might be present. Such rigorous containment prevents any exposure of workers or the surrounding public to radioactivity, which is confirmed by continuous monitoring. A combination of remote operation of parts of the facility for handling waste, which are generally located at basement level, together with additional shielding by walls, effectively ensures direct radiation doses not only meet standards, but are as low as reasonably achievable (ALARA). The assessment of the normal state includes all operations involving waste acceptance, inspection, encapsulation, handling, interim storage, transportation and disposal (See Section 5.3).

To assess abnormal operations, perturbations that could lead to leakage of radioactivity from HLW or TRU waste are assessed, using event trees that include both natural phenomena and human events that could cause sequential loss of the multiple layers of protection to prevent such events. Where possible, failsafe counter-measures are introduced to prevent such perturbations and, in the event of failure, mitigation of the consequences (see Section 5.4.1). For abnormal operation scenarios (e.g., fire or waste package drops) conservative numerical analysis is used to determine if this could credibly lead to leakage of radioactivity (see Section 5.4.2). A conclusion from the scenarios examined to date is that loss of containment is extremely unlikely in all analysed cases. This is further addressed in Section 7.2.2, in terms of the results of the safety assessment.

When sites become available, the operational safety assessment will be specifically tailored to them, with special consideration of common mode failures, which have been little examined so far. Additionally, feedback from the safety assessment will guide refinement of design and associated safety measures, to assure meeting the legal requirements for both radiological and general occupational safety.

(ii) Post-closure safety

Unlike the case before closure, post-closure safety of the repository relies on a passive system of multiple engineered and geological barriers. Even through post-closure monitoring may be implemented; this is not required to assure safety. A key to assuring safety is siting in a stable geological setting, where required safety functions can be assured for a sufficiently long period of time. In such a site, the repository is designed including an EBS with safety functions to complement those of the local geology. Furthermore, even if specific perturbing events and processes may occur that degrade future barrier performance, their probability and radiological consequences should be sufficiently low that regulatory standards are met. If the assessment shows safety cannot be assured with confidence, the design of the repository may be modified or, if this is insufficient, the site will be rejected. As regulatory standards have not been specified, the methodology and technical basis developed in this report is prepared to allow adjustment when such standards are available.

As described in Chapter 6, based on the system understanding incorporated in the SDMs and the associated repository designs, scenarios that reflect potential future evolutions are developed. Base scenarios that describe expected evolution are complemented by variant scenarios, which capture inherent temporal and spatial variability of evolution of the repository in its geological setting and also account for uncertainties in system understanding and in associated models and databases. Variant scenarios are considered to be less probable than the base scenarios, but their likelihood is not quantified at the present time. However, for major perturbations, the very low probability involved is estimated to the extent possible. When indicative probabilities to these major perturbation scenarios can be quantified, this, together with the calculated dose, can be compared with the risk target for very low probability scenarios (see Section 6.1.5).

RN release and transport models account for the composition and geometry of the EBS, the layout of the disposal panels and the spatial heterogeneity of the geological setting in terms of hydrogeology and solute transport characteristics. A three-dimensional groundwater flow/solute transport model has been used, which can better evaluate the performance of the near-field. This is intended to more realistically evaluate the effects on post-closure performance resulting in differences in the repository design and its geological setting for specific sites. Such realistic assessment also provides important feedback for planned optimisation of the designs. Since the detailed analyses to improve realism may involve large computational loads, 3D models currently cover only a limited area of the near field, but expansions are ongoing, in line with increased power of parallel computers, with the aim of better assessment of release and transport on the scale of entire sites. Depending on the analysis objectives, processes to be considered, boundary conditions, configurations, etc., it is important to apply codes that do not require as much computer power.

Current models/databases introduce conservative simplifications, especially with regard to treatment of uncertainty, to ensure the robustness of the safety assessment. In particular, the chemical-thermodynamic models, used to derive porewater chemistry in the EBS, elemental solubility limits and speciation (that support selection of RN migration parameters such as sorption and diffusion coefficients), are inherently unrealistic in that they assume equilibrium that is rarely found in nature. Nevertheless, a description of RN release and transport can be developed that is consistent with that in other safety assessments and compatible with observations in relevant analogue systems.

The RN release and transport models are adapted for use in the consequence analyses of base, variant and unlikely perturbation scenarios, quantifying the RN releases used for dose assessment (see Section 6.4). Stylised inadvertent human intrusion scenarios are also developed, in line with recommendations of international organisations and those used in other national programmes, with scoping RN release and transport models used to estimate potential dose impacts (see Section 6.5).

(iii) Current status and future needs

As described above, the H12 safety assessment methodology has been further developed in light of evolution of international discussions on regulations for geological disposal as well as those for other nuclear facilities. Additionally, considerations both pre- and post-closure of repositories tailored to representative SDMs are now included. This will form the basis for assessment of specific sites after the LS stage is initiated. More realistic, site-specific safety assessment will provide a basis for comparing repository design options and, possibly, comparing different potential host rocks at a specific site or assessing pros and cons of different sites.

Specifically for the assessment of operational safety, the hazard database will be updated in the light of experience in Japan and overseas, expanding current knowledge about potential perturbations to normal operation and representation of these in abnormal operation scenarios. In particular, assessment of scenarios involving common mode failure will be expanded, widening the range of scenarios for abnormal events (such as waste drops and fire) and improve consequence analysis, with associated verification and validation of the models used.

In addition to more realistic 3D models of RN release and transport over larger scales, as noted above, a future aim is to capture post-closure evolution of the repository system with time (“4D modelling”). This will require a model that can simulate the evolving distributions of thermal, hydrogeological, mechanical, and chemical (THMC) conditions in detail, along with the impacts of these on the EBS evolution and the RN migration characteristics of the flow path from the EBS to the GBI. This allows consistent assessment from construction, operation and closure of the repository to the period after closure, so that the results of the safety assessment can be appropriately fed back to the evolving design, taking into account advances in technology over this period. Parameters to define RN transport must reflect long-term changes in the surface and deep environment over time, which are not considered in this report and depend on input from characterisation of specific sites. As a starting point, 4D SDMs that take into account climate and sea-level changes, which are already under development, will be used, as described in Section 7.2.1 (1) (iv). In particular, site-specific 4D

SDMs will more explicitly reflect changes in the GBI, which has a large impact on assessment of the doses resulting from most release scenarios. This requires better definition of the flow paths that lead from the EBS to the surface environment, along with their RN transport characteristics, which will require both focused laboratory studies and in-situ tests in URLs. In addition, site-specific biosphere models will be developed that are tailored to both the present and likely future physical setting and lifestyle of local populations. A special focus in all such work will be extension of the work included in this report, implicitly assuming a disposal footprint under land, to the very different hydrogeological and geochemical conditions that may be encountered for disposal panels offshore for a likely coastal repository setting.

Finally, with the aim of facilitating future assessments, a goal will be to utilise advanced technology for managing knowledge, information, and data related to scenario construction, model development and data setting, together with visualising these within storyboards and animations. This will require close coordination of geological characterisation, repository design, and safety assessment, increasing traceability and facilitating uncertainty/sensitivity analyses and quality assurance, all leading to improving the reliability of future safety cases.

7.2.2 Evaluating the safety of geological disposal

As mentioned in Section 7.1, the assessment basis developed in this report, under current boundary conditions, does not yield a safety case for specific sites, but rather illustrates the fundamental feasibility of demonstrating safety for designs tailored to representative siting environments. The safety assessment thus highlights issues that need to be considered to determine if any volunteer site would be suitable, and also could lead to a specific safety case that meets regulatory standards to be specified in the future, while identifying open issues that need to be clarified by future R&D. Here, the results of the safety assessment will be discussed, with the aim of identifying such issues.

(1) Safety assessment results

(i) Operational safety

(a) Normal operation

Chapter 5 assessed operations within a repository specified in Chapter 4, with a focus on radiological protection of the general public. Under normal operating conditions, the radiation dose at the boundary of the site was significantly lower than the dose target value (50 μ Sv/y) for general public stipulated in the Business License Standards Regulations (see Section 5.3). If it is difficult to ensure a sufficient distance to the site boundary for specific sites, this can be readily managed by increasing the thickness of shielding walls and/or re-arrangement of surface facility layout. Extensive experience in the nuclear industry will assure that all operations and equipment avoid any risk of loss of containment during any of the perturbations that must be considered during normal operations, which is particularly facilitated by the robustness of the waste packages considered.

So far, the influence of topography and the surface environment on surface facilities is not considered, with the reference case layout on a large flat area above the disposal footprint. For specific sites, the available area for the surface facility may be small, it may not be flat, and may be located at a distance from the optimal disposal footprint, further constrained by economic and social aspects. Many of these issues are common to the design of other nuclear facilities, and it is considered possible to flexibly deal with them by combining system understanding with accumulated experience in Japan and overseas.

(b) Abnormal operations

In assessment of the radiological effects of anomalous conditions in surface and underground facilities that handle waste, constraints set by countermeasures that minimise likelihood or possible impacts, are taken into account. For example, interlocks to reduce the risk of dropping wastes and physical lifting height limits that define the worst case drop for all relevant perturbations (see Section 4.6.2 (6)). Assuming that safety measures to prevent accidents fail, illustrative scenarios were developed for both HLW and TRU repositories and their consequences evaluated. In all of the cases examined, it has been confirmed that there is no predicted release of radioactivity (see Sections 5.4.2 and 5.4.3). All designs and operational processes assessed are commonly applied for the three SDMs. For specific sites, this assessment will be extended and tailored to the repository and operating processes involved, taking account of advances to allow more realistic scenario specification, considering also potential common mode failures.

(ii) Post-closure safety

In this report, a risk-informed strategy is adopted, with distinction between the probability of the base, variant and low probability perturbation scenarios, which are complemented by stylised human intrusion scenarios, with target dose assigned to each (see Section 6.1.5).

(a) Assessment of base and variant scenarios

The base scenario represents the expected evolution of a well-sited and designed repository, assuming all safety functions perform as required, while variant scenarios scope the range of scientifically reasonable uncertainties in the associated assumptions, models and data (see Section 6.3.3 (2)).

Quantitative consequence analyses of such scenarios, for all SDMs and corresponding repository designs, show that the maximum total dose occurs within 100 ky and is well below the set target (10 µSv/y) for the base case (see Section 6.4.1). In addition, no variant scenarios are near the set dose target (300 µSv/y), which is internationally recommended as an indicator for repository safety (see Section 6.4.2). The results also show that, for all three SDMs and two model groundwaters, the HLW options H12V and PEM system result in effectively the same maximum dose. For TRU waste, the maximum dose in the package A case was slightly higher than that of Package B. Thus, Figure 7.2-3 for H12V co-disposal with TRU waste package A, shows the maximum doses calculated.

Figure 7.2-3 shows differences in maximum dose compared to the base case for many of the variant cases, predominantly due to scenarios in which I-129 and U-233 are assumed present as anions with high solubility and extremely small sorption onto both buffer and host rock, in which resultant doses are little impacted by other varied parameters.

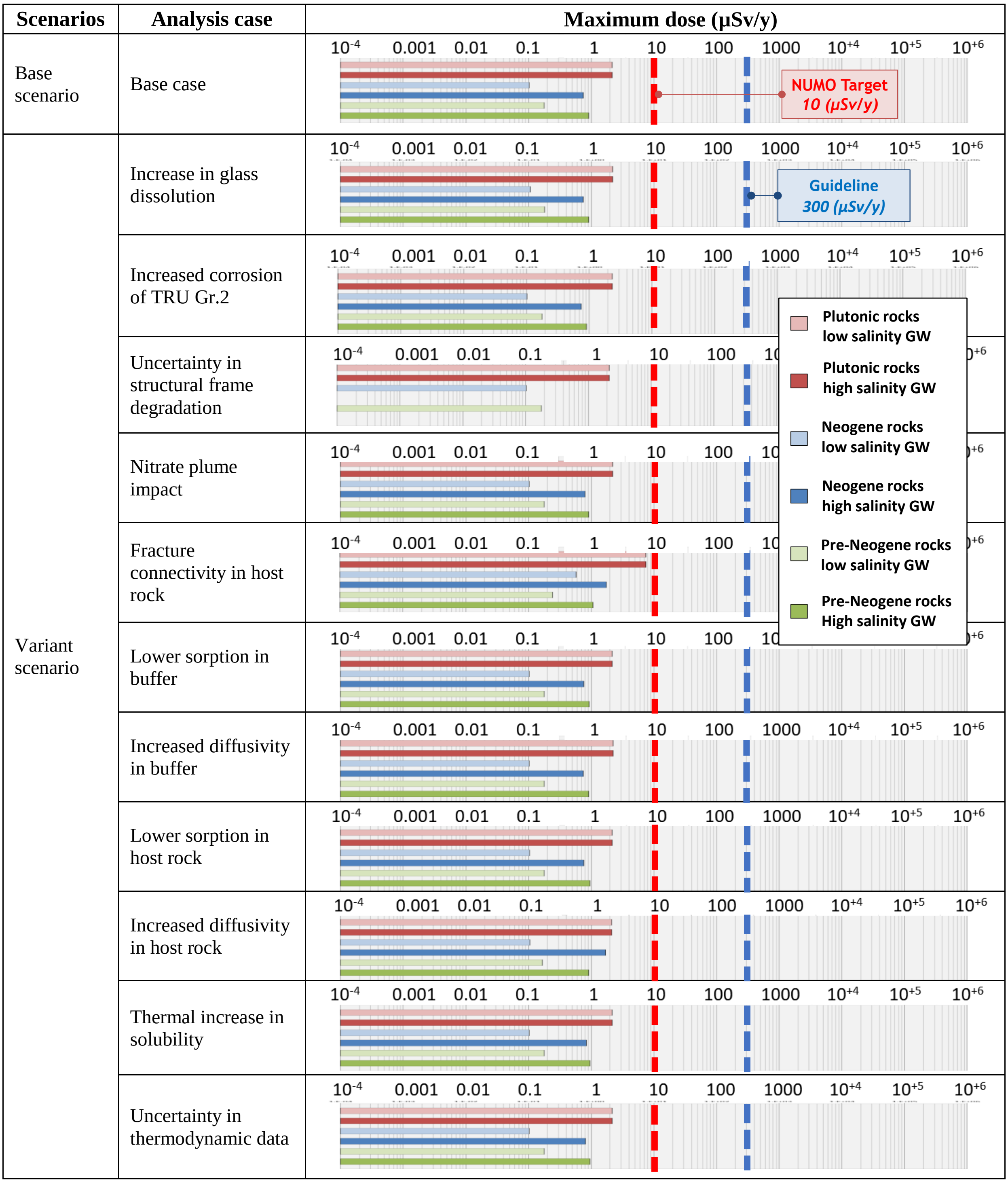


Figure 7.2-3 Base and variant scenario maximum doses for the analysis cases of co-disposal of HLW (H12V) and TRU waste (package A)

(b) Assessment of human intrusion and low probability perturbation scenarios

Although the likelihood of a major perturbing event is very low given proper site selection and facility design, in Japan these cannot be precluded for the very long timescales under consideration. Hence, assessment is carried out to determine their potential radiological significance and assess robustness despite associated uncertainties. In particular, volcanic and seismic activities were targeted, developing very conservative scenarios of a new volcano occurring directly beneath the repository and a major fault growing until it intercepts the repository at some point in the future. Calculated maximum doses for these scenarios are shown in Figure 7.2-4, compared to the defined targets (in the first year: < 20 - 100 mSv, thereafter: < 1 - 20 mSv/y). In addition, the probability of occurrence of such events was estimated and total risk calculated by converting dose into the probability of occurrence of lethal cancer or serious genetic effects and the result compared with a risk target of < 10^{-5}/y which corresponds to the internationally recommended dose constraint (300 µSv/y). In no case were the dose or risk limits reached (see Section 6.4.3).

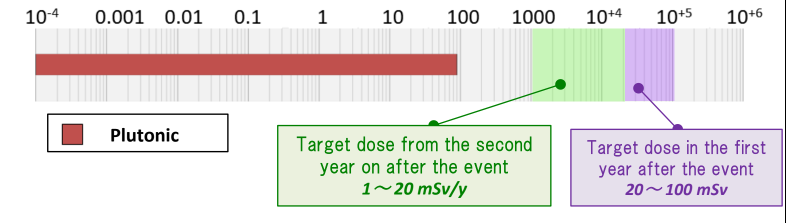
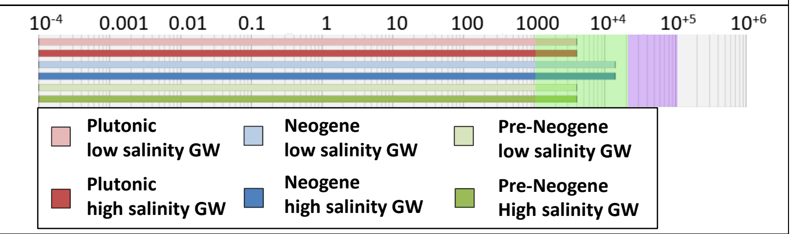
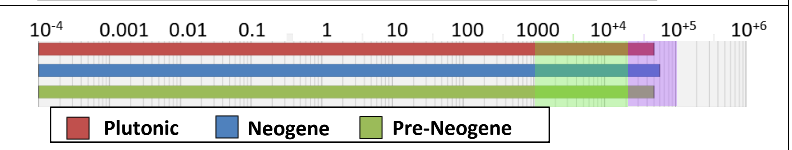
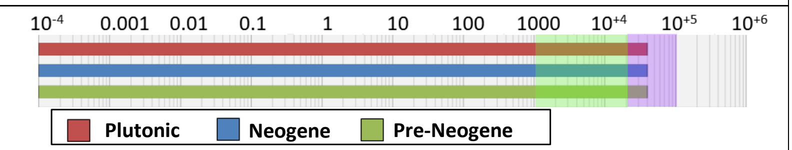
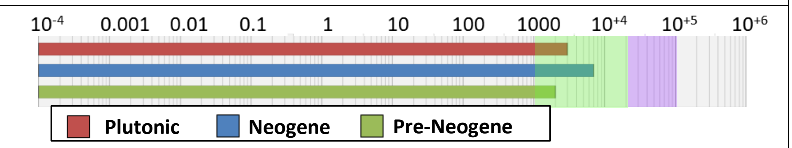
Scenarios	Analysis case	Maximum dose (µSv/y)
Low probability scerarios	New volcanism (dose assessment results for a repository in plutonic rock – high density disposal)	
	Fault extension	
Human intrusion scenarios	Borehole worker exposure (observation of excavated spoil)	
	Borehole worker exposure (observation of core)	
	Migration of nuclides in borehole	

Figure 7.2-4 Maximum doses for human intrusion and low probability scenarios (Co-disposal of HLW (H12V) and TRU waste (package A))

The probability that future human actions will affect the safety function of the repository is judged to be very low due to disposal at depths greater than 300 m and avoiding locations containing economically valuable mineral resources during site selection. It is expected that the probability will be further reduced by institutional control measures, such as keeping records and prohibiting some activities on the site – e.g., at least by the time of final decommissioning and release of the site from institutional control. To evaluate possible radiological effects, stylised human intrusion scenarios were assessed, based on borehole drilling as it occurs in Japan today. Both the calculated maximum doses (Figure 7.2-4) and assessed total risks lie well below the targets defined for low probability perturbation scenarios above (see Section 6.5).

In the future, such analysis will be refined for site conditions, accounting for expected geological evolution and the possibility of several perturbations occurring together.

(c) Conclusions from safety assessment

The three SDMs and the repositories tailored to them are expected to be representative of suitable sites in Japan that could result from the site selection process. The robust arguments developed above, adopting conservatism to account for uncertainties, form a good basis for assuming that operational safety can be assured for both normal and perturbed states. After closure, uncertainties generally increase with time, but there is reasonable confidence that these will not preclude demonstration of safety for suitable sites, especially with emphasis on the period during which the toxicity of the waste is of most concern (≈ 100 ky). Nevertheless, there are limitations to the post-closure assessment that have been identified and will need to be addressed in order to meet the requirements of a safety case to support selection of sites after the LS stage is complete.

One important limitation is the assessment of scenarios including uplift and erosion. By appropriate site selection, sufficient uplift and erosion to impact a deep repository in the first 100 ky should be excluded. However, in Japan, this cannot be precluded over much longer timescales. The impacts of such scenarios are highly site-specific, depending not only on uplift/erosion rates, but also geological structure, topography/bathymetry, impacts of glacial cycles and the slow evolution of the repository system as depth of overburden gradually decreases or increases (e.g., as may occur under the sea). On the basis of information derived from the stepwise siting process after the LS, appropriate scenarios will be developed, along with the tools and databases required to quantify them.

Representation of the processes resulting in RN release and transport, in both the base and variant scenarios, has been constrained by both lack of sufficiently detailed geological information for the different spatial scales considered and also the capabilities of current models, codes and computers. Using site-specific information and next generation models, significant improvements in realism can be introduced. For example, assessing RN migration on a repository scale (several km x several km) would be a great advance compared to assuming unrealistic LDF short circuits to the GBI (see Section 6.4.1 (5)). When combined with more detailed 3D (or 4D) solute transport models at panel/repository scales, under development by extending the present model for near-field scale, the degree of conservatism should be significantly reduced, which should be reflected in better performance of both the engineered and natural barriers. The degree of improvement of models depends also on general advances in computing technology, which will be continuously monitored.

As volunteer sites are likely to be located in coastal settings, further major improvements required involve the development of scenarios and assessment tools for repositories with waste disposal footprints partially or completely below sea rather than land, together with 4D SDMs explicitly representing the impacts of sea level change. In general, it would be expected that performance of a subsea repository would be greatly improved by negligible hydraulic gradients, but variations in hydrogeology and geochemistry for disposal zones that vary between being under land or sea may complicate analysis (but would still allow development of a rigorous safety case, as shown in Sweden [27] and Finland [28], where current sites may be under the sea in the future).

Finally, stylisation that takes into account site conditions is essential for scenarios related to low probability perturbation and future human actions, which may also need refinement to reflect guidelines set forth in the safety regulations that will be formulated in the future.

(2) Supporting arguments for post-closure safety

The formal safety assessment and comparison of calculated doses (or risks) with a target is a necessary, but not sufficient, argument of the safety of a particular repository. Quantitative assessment inevitably involves much simplification of the real system and hence a safety case must include additional arguments that support conclusions reached, as also presented in the H12 report. Here, such supporting arguments are developed for both the assessment basis and safety assessment presented in this report.

(i) Safety arguments based on complementary indicators

In the safety assessment described in Chapter 6, dose is used as the main index to assess safety, estimating the radiological effects on humans by evaluating this parameter as calculated by release rates of RNs to a highly stylised GBI/biosphere. Since the uncertainty related to future human lifestyles and the characteristics of the surface environment are extremely large, it is important to show the performance of the geological disposal system using other indicators that do not depend on these factors. Such alternatives to dose are termed complementary indicators (see Supporting Report 7-1) and have been used both in Japan and other countries to support safety cases. Here examples of these are presented to support arguments for the safety of the repositories specified in Chapter 4.

(a) Arguments to support repository containment performance

The basic safety feature of RN containment within repositories tailored to the SDMs can be well illustrated by the base case RN migration analysis described in Section 6.4.1, focusing on the distribution of total radioactivity within the repository system (described in detail in Supporting Report 7-2). Figure 7.2-5 shows an example, distinguishing between the activity located:

- Inside the panel scale region (EBS and immediately surrounding rock).
- Outside the panel scale but within the repository scale geosphere.
- Outside the repository scale region.

The assessment is for the base case for co-disposal of HLW (H12V – which is little different to the PEM: Section 6.4.1 (7)) and the more conservative (lower performance) TRU waste package A, distinguishing between the 2 model groundwater variants.

Figure 7.2-5 presents result up to 10 My, despite the fact that the models are extremely uncertain (or inapplicable) beyond 1 My and, by this time the total radioactivity has been greatly reduced by radioactive decay. For the plutonic case, ≈ 99% of the overall radioactivity remains within the panel scale region after 1 My, regardless of the model water chemistry. For the Neogene and Pre-Neogene sediments, performance is similar for the lower salinity groundwater. For the high salinity groundwater, both sediments show radioactivity release from the panel scale is about 1% after ≈ 100 ky, with about 30% loss for the Neogene sediments and about 25% for Pre-Neogene sediments after 1 My. Even then, the release from the repository scale at 1 My is only about 20% for both the Neogene and the Pre-Neogene sediments.

This clearly shows that the repository maintains containment in terms of high retention for the period of concern. In the future, however, it will be important to confirm such performance using more realistic models that take into account evolution of the repository system.

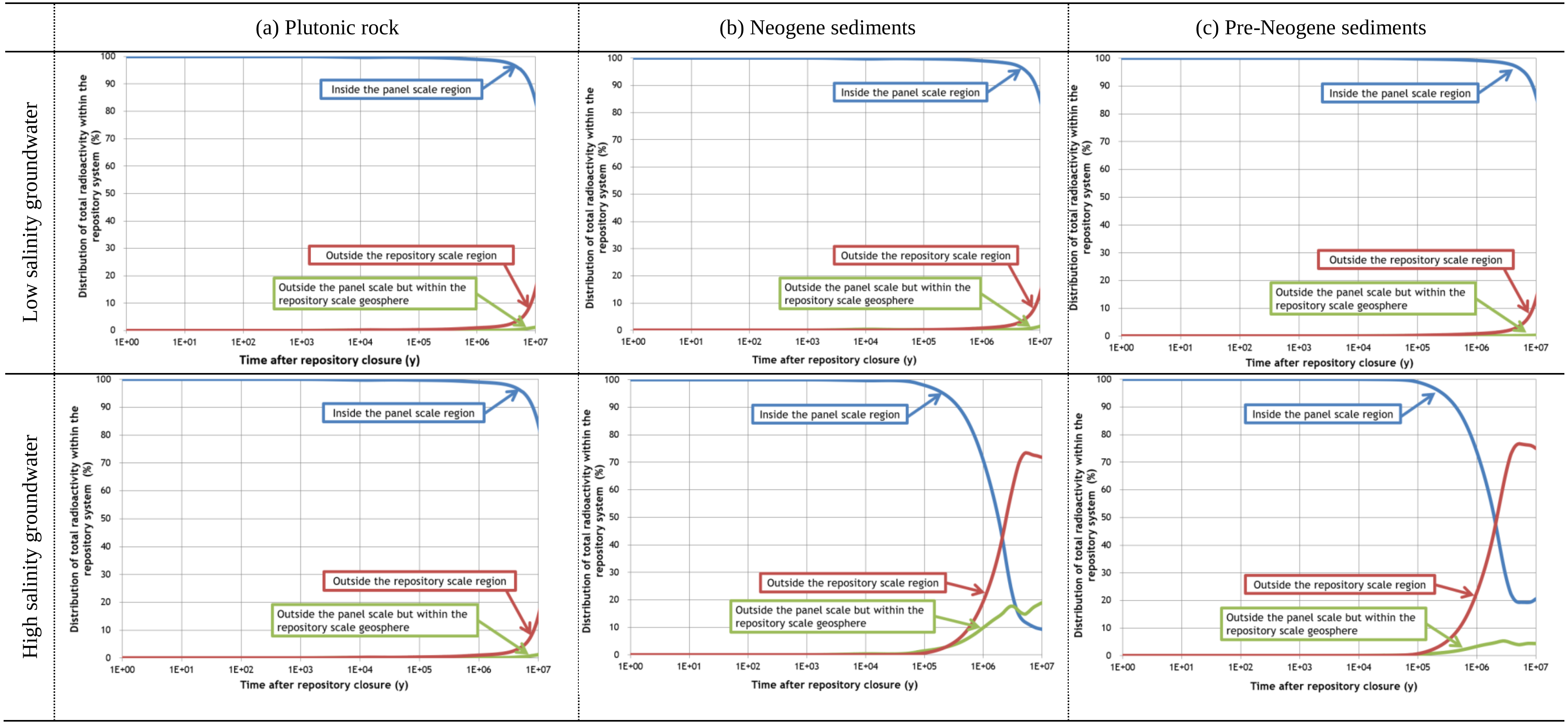


Figure 7.2-5 Distribution of radioactivity in different repository regions
(Base case for co-disposal of HLW (H12V) and TRU waste (package A))

(b) Arguments to support radiotoxicity reduction with time

As shown above, almost all radioactivity is contained within the panel scale region for 100 ky for all base case calculations. To put this in context, potential radiotoxicity [29] is calculated as an alternative indicator of radiological hazard. This is derived by multiplying the quantity of each radionuclide present by the dose conversion factor for oral ingestion. Although it is clearly impossible for such material to be orally ingested, this is often used as a yardstick for potential radiological hazard

For each of the cases shown in Figure 7.2-5, calculated potential radiotoxicity of RNs remaining in the panel scale region is presented in Table 7.2-1. This involved calculation of potential radiotoxicity of the entire panel scale region (Sv) for both the HLW and TRU waste repositories, with radionuclide content derived from the migration analysis and dose conversion factors for oral ingestion taken from ICRP [30].

Table 7.2-1 Average potential radiotoxicity within the panel scale area at 100 ky after closure (base cases)

Unit: Sv/kg

Host rock	Plutonic rocks		Neogene sediments		Pre-Neogene sediments	
Water chemistry	Low salinity	High salinity	Low salinity	High salinity	Low salinity	High salinity
HLW repository	1.2×10^{-2}	1.2×10^{-2}	9.5×10^{-3}	6.5×10^{-3}	8.3×10^{-3}	7.3×10^{-3}
TRU repository	4.2×10^{-2}	4.2×10^{-2}	2.7×10^{-2}	2.7×10^{-2}	4.3×10^{-2}	4.3×10^{-2}

Natural uranium ore	
Cigar Lake [31]	2.5
Ningyo-toge [32]	2.4×10^{-2}

While the panel scale areas defined in Section 3.3 extend 100 m downstream with 50 m vertical extent above and below this area, the volume to calculate potential radiotoxicity is conservatively set by neglecting downstream extension. The average potential radiotoxicity per kg (Sv/kg) was calculated, assuming this entire volume is rock, which dominates over the volume of the EBS and using appropriate densities (plutonic rocks: 2.69 Mg/m^3, Neogene sediments: 2.28 Mg/m^3, Pre-Neogene sediments: 2.64 Mg/m^3) as described in Supporting Report 7-3. Table 7.2-1 additionally includes for comparison, potential radiotoxicity calculated for ores from the Canadian Cigar Lake [31] and Japanese Ningyo-toge [32] deposits, with uranium contents of about 8 % and 0.05 %, respectively.

From the table, it is clear that the potential radiotoxicity calculated in this way, is sensitive to the repository layout, which results in values in the smaller TRU facility greater than the more extensive panels for HLW, and in Neogene sediments less than for the other rocks. In any case, the potential radiotoxicity of the repositories is far below that of Cigar Lake uranium ore, being similar to the uranium ore of Ningyo-toge.

Taking (a) and (b) together, at about 100 ky after repository closure, most radioactivity remains in and around the EBS and, by then, its potential radiotoxicity is similar to lower grade uranium ores.

(c) Arguments on potential radiotoxicity of releases into the biosphere

To complement the arguments on the effectiveness of the containment safety function, a perspective on the significance of any releases to the surface can be provided by indicators that do not depend on very uncertain assumptions about the food chains and lifestyle that are required for biosphere dose calculations. As an example, the impact of such releases can be evaluated by assessing the case of these occurring directly into a river.

Specifically, calculated maximum base and variant case RN releases from the repository scale regions (Sections 6.4.1 and 6.4.2), given in Bq/y, are assumed to go directly into a typical Japanese class A river, with the same volumetric flow as assumed for the Chapter 6 biosphere model (1×10^9 m^3/y, see Supporting Report 6-1) [33]. The resulting average RN concentrations [Bq/m^3], are assessed using the ICRP dose conversion factor for internal exposure by ingestion [30] and summed to derive potential radiotoxicity (Sv/m^3). This calculation process is described in detail in Supporting Report 7-4.

The results are presented in Figure 7.2-6 for co-disposal of HLW and TRU waste, which is compared to the World Health Organisation “Guidelines for Drinking-water Quality” [34], taking the U-238 guideline values for a concentration limit (<10 Bq/l) and converting this into a potential radiotoxicity. From this figure, it is clear that, in all cases, the potential radiotoxicity from repository releases is very small compared to the limit for natural RNs in drinking water.

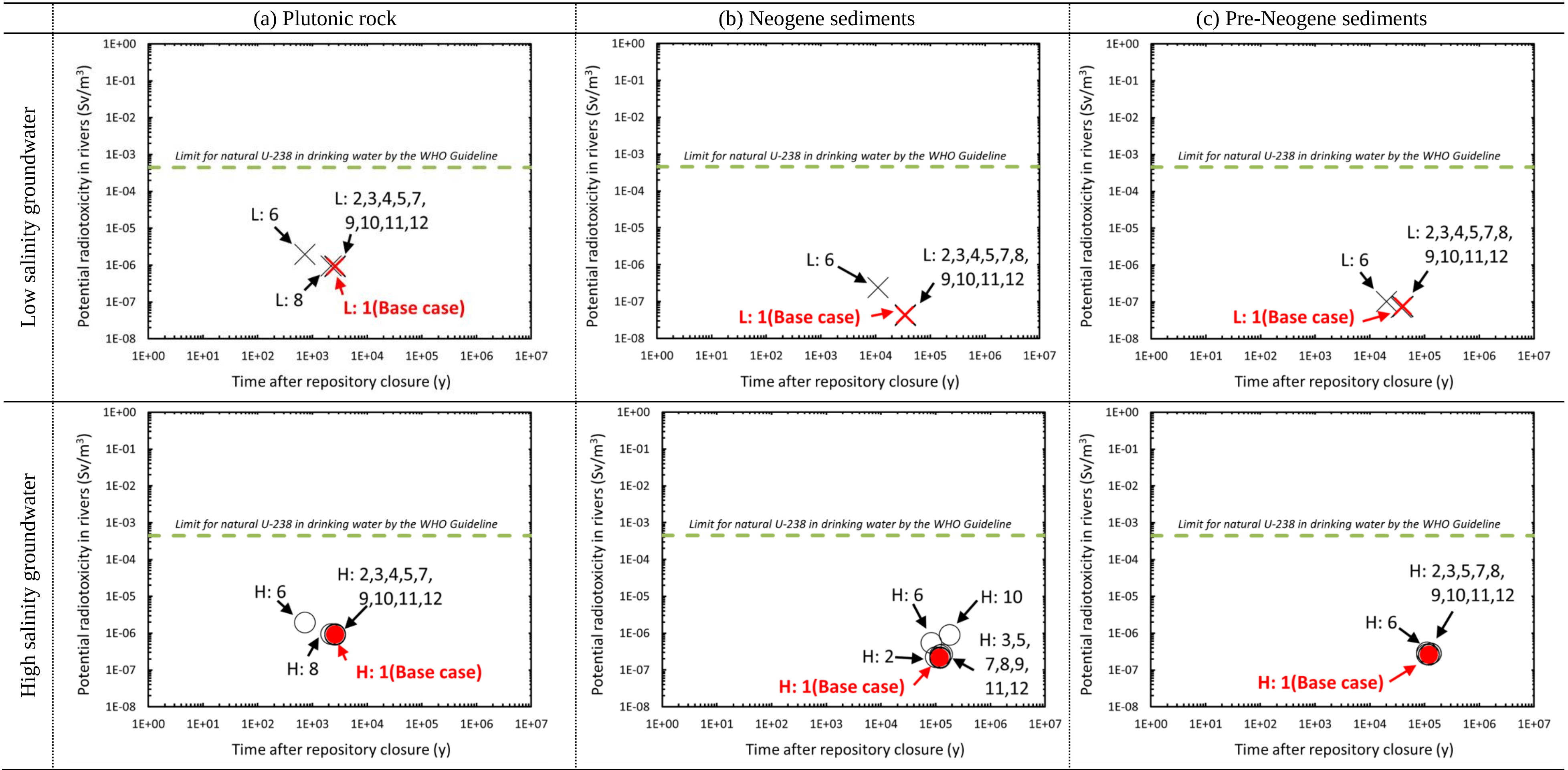


Figure 7.2-6 Potential maximum radiotoxicity in rivers based on base and variant case concentrations (co-disposal of HLW (H12V) and TRU (package A)) (L: low salinity groundwater, H: high salinity groundwater, number: variant case numbers given in Table 6.4-6 of Section 6.4.2)

(ii) Supporting arguments from natural analogues

The extent to which repository safety functions can be validated by short timescale laboratory studies of subsystems or in-situ experiments in URLs is inherently limited. Such experiments are used to the extent possible to test the assumptions, models, and data sets used to assess safety. However, these need to be extended using natural analogue test cases that cover appropriate timescales and the complexity of the natural environment, as discussed further in the following and in Supporting Report 7-5.

(a) Natural analogue arguments supporting long-term geological stability

In some national programmes, natural analogues have been used to demonstrate the fundamental feasibility of geological disposal based on the ultra-long-term (Gy) stability of uranium ore bodies in particular settings (e.g., Oklo, Cigar Lake [31]). Although no rocks of anything like this age are found in Japan, the fundamental principle of stability of geochemical anomalies in deep, chemically-reducing environments is applicable. The requirement is thus to illustrate that stability is sufficient to support safety arguments over My timescales, when site selection excludes areas vulnerable to volcanic and/or tectonic perturbations and uplift and erosion, as discussed in Chapter 3. Such natural analogue arguments are based predominantly on paleo-hydrological and geochemical studies.

Unlike the cases in countries where the host rock extends from repository depth to the surface (e.g., in Canada or Fennoscandia), in Japan – as captured in the SDMs – low permeability host rocks are generally overlain by a range of more permeable sediments. Even in areas with significant topographic relief, such a situation tends to decouple very slow groundwater flow at depth from more rapid flow in overlying aquifers. For example, studies in the Horonobe area demonstrated that deep Neogene sediments contain very old, stagnant saline water, with a calculated age of about a few My, where mass transport is dominated by diffusion, despite changes in chemical conditions that are clearly observed at shallower depths. The low impact of moving saline-fresh water boundaries associated with long-term climate/sea-level changes in this location [35][36][37] indicate that, for coastal sites, the impacts of such changes may be minor in the repository host formation.

This conclusion is consistent with observations at the Tono uranium mine, where uranium ore has been preserved in Neogene sediments for about 10 My. This is explained by a stable hydrogeological setting in which pH and reducing conditions are buffered by interactions between water, minerals and microbes [38]. There is no isotopic evidence of uranium mobilisation as a result of natural perturbations, such as uplift and erosion, or sea-level changes [39]. Indeed, despite evidence of movement of faults that penetrate ore bodies, there are no indications of either uranium or its more mobile daughters being lost.

It can be noted that such analogue arguments also imply that the scenarios examined to determine impacts of future fault movement, or even impacts of human intrusion, are over-pessimistic. In the event of a short circuit flow path being formed, typical geological settings in Japan would not result in any significant flow either upwards or downwards through a repository and, even if there was a short-term geochemical perturbation, this would be buffered back to original conditions by biogeochemical reactions. There is further evidence to support such a conclusion, such as analytical study of calcite crystallisation at the surface of water conducting fractures. These indicate that the chemical conditions of groundwater remain virtually unchanged on a My timescale at depths of 320 m – 610 m in the granite bedrock of Tono, despite the presence of a major fault zone [40].

Over safety-assessment timescales, therefore, there are good arguments to support expectations that suitable host rock settings should provide adequate protection of the EBS. One caveat here, however, is that artesian conditions could occur in some sedimentary host rocks that are underlain by more permeable formations. These would generally be identified during site characterisation, but even this case would not necessarily preclude sufficient host rock performance for a low permeability sediment – as demonstrated, for example, by the Swiss Opalinus Clay in which solute transport occurs by diffusion despite a very high vertical hydraulic gradient and the presence of fractures [41].

In addition to its prime role of protecting the EBS, there is also analogue evidence suggesting that the natural barrier performance in terms of limiting RN mobility may be greater than currently assumed. A good example here is based on careful studies of the limiting concentrations of U and Th in the old groundwaters found at Horonobe and Mizunami [42]. Although not clearly explainable based on chemical thermodynamic models, measured concentrations in true solution (using filtration to remove colloids) is ≈ 10^{-12} mol/l for U and ≈ 10^{-13} mol/l for Th – vastly below the solubility limits set in Section 6.4.1 (≈ 10^{-6} mol/l for U and ≈ 10^{-8} mol/l for Th). Even though it is unclear if such observed concentrations represent equilibrium solubility set by an undefined mineral phase or a steady state representing slow rock-water interactions, such values indicate that some input parameters used in the safety assessment may be highly over-conservative [43]. Nevertheless, care must be taken extrapolating such information to a specific site as, especially for Th, elemental concentrations in groundwater are predominantly in the form of suspended particles or colloids, indicating that potential transport of such phases would also need to be explicitly considered.

Even though a geological setting may be stable, it also has to be shown that the presence of the repository does not degrade favourable properties. In the case of argillaceous sedimentary host rocks, a particular concern is alteration of minerals along flow paths due to the high pH of leachate from concrete – particularly for the TRU disposal area. Several natural analogues allowing assessment of long-term interaction of hyper-alkaline plumes with sedimentary rocks present a consistent picture, supporting arguments that alteration reactions are slow and the products of these are generally as expected from models, although secondary mineral assemblages differ in detail. For example, at the Maqarin site in Jordan, hyper-alkaline water (up to pH 12, similar to Portland cement porewater) has been in contact with natural clays for at least 80 ~ 100 ky, but alteration is seen to be restricted. In particular, water conducting fractures are observed to seal due to precipitation of secondary minerals, which limits alteration of host rock to within 3 - 4 mm of such features [44][45]. Migration of plumes over longer distances occurs only if there is a mechanism for reactivation of sealed fractures, which can be expected to be limited at repository depth in a stable tectonic setting.

(b) Natural analogue arguments supporting EBS barrier roles

As noted already in the H12 report, the EBS developed for HLW is very robust and assures high containment of RNs for any reasonably stable geological setting. Such high performance is assured by mechanistic understanding, empirical laboratory data and supporting analogue arguments.

Laboratory studies show dissolution of HLW glass in contact with water is slow, with kinetics influenced by dissolved silica concentration. Additionally, dissolution tends to decrease with time as protective alteration layers build up (involving minerals such as palagonite) – which can be particularly important for larger glass blocks. Such processes can be seen in analogues and, for the particularly relevant case of glass within a Japanese argillaceous rock similar to compacted bentonite, studies of shards of 1 My old glass in contact with saline groundwater (pH ~ 8, Eh ~ -50 mV) have been studied. Here, despite being so small that alteration layers are not significant, persistence of the glass can be related to the very low water flow rate and resultant high silica concentration (equivalent to amorphous SiO_2 saturation) [46][47][48].

Although conclusions must be drawn with care due to chemical differences between analogues and HLW glass – and also the absence of significant RN concentrations in the former – the large empirical database suggests that the lifetime of HLW glass assumed for safety assessment based on laboratory experiments (~ 70 ky, see Section 6.4.1 (2) (v) (b)) is very conservative. Indeed, for a fractured monolithic block within protective Fe corrosion products and a bentonite diffusion barrier, a lifetime of at least an order of magnitude greater than this value might be more realistic.

The carbon steel of the overpack is also thermodynamically unstable and could reduce water in the absence of any stronger oxidants. In relevant geochemical environments, however, Fe corrosion is kinetically slow and may decrease to negligibly low values as protective oxide layers build up. This is supported by a large number of natural analogues based on archaeological artefacts. Indeed, even in more corrosive environments, protective coatings may assure the longevity of large steel objects. This is well illustrated by a hoard of Roman nails of low carbon steel discovered in Inchtuthil, Scotland, where nails with very low corrosion rates, or even survival without corrosion for almost 2 ky, were observed in central parts of the hoard. Despite an environment with weakly acid, oxidising water, corrosion of outer nails produced an alteration layer with which chemically reducing/low flow rate conditions protect those within [49].

Such qualitative observations are consistent with more quantitative analyses of the corrosion of Japanese archaeological iron artefacts buried near surface for a few hundred to about a thousand years. Corrosion depths lie in the range of between 0.2 mm and 5 mm, which is interpreted as due to formation of protective corrosion alteration layers [50][51]. Under repository conditions, where any oxygen introduced during the construction and operation period will be rapidly consumed, the long-term corrosion rate of the massive overpack is thus expected to be very low, giving containment lifetimes much longer than the times in excess of 10 ky calculated and presented in Chapter 4.

The clay minerals in bentonite, the main constituent of buffer and backfill, are generally stable under the conditions found in Japanese host rocks and, indeed, are often components of the sedimentary host rocks or found as alteration infill in fractures in plutonic rocks. Although these may degrade at higher temperatures, an extensive analogue database supports arguments that such alteration occurs only in the presence of water, is generally constrained by supply of K and, even when this element is abundant, is very slow at temperatures below about 120 – 150 °C. Hence the key roles of the HLW buffer can be assured over assessment timescales of > 100 ky as long as the groundwater water composition is not significantly altered and the emplacement quality can be assured (which can be strongly supported for the PEM, in particular).

The longevity of bentonite is less assured in the presence of significant quantities of cementitious materials (e.g. for buffer around TRU waste), as the component clay minerals are thermodynamically unstable at high pH, just as discussed above for sedimentary host rocks. Several natural analogues allowing assessment of long-term interaction of hyper-alkaline plumes with natural bentonites present a consistent picture, further supporting arguments that alteration reactions are slow and the products of these are generally as expected from models. For example, bentonite mines in the Mangatarem region of the Philippines, allow study of long-term interactions with highly alkaline and high Ca content water with a pH of between 9.3 and 11.6 (similar to that resulting from low-pH cement interactions). Alteration zones in bentonite are quite limited (generally within 5 mm), predominantly due to the formation of a protective low-permeability, iron-rich layer (3 mm) [52]. Although details of thermodynamic alteration models are not confirmed, these analogues provide good support for assuming bentonite retains its barrier roles for timescales much longer than ≈ 100 ky.

Concrete and other cementitious materials used as TRU waste immobilisation grout, emplacement cell infill, backfill and to form structural components, are also thermodynamically unstable and will alter by interaction with groundwater and other materials present – e.g. bentonite (as considered above), steel, organic materials, etc. Again, an extensive archaeological analogue database supports arguments that such alteration is slow and key properties (e.g., high pH, low permeability) will persist for timescales from thousands to hundreds of thousands of years, depending on the local hydrogeological environment.

Despite the extensive analogue support for assumed high performance of the HLW EBS, the situation for TRU waste is less complete – which is reflected in the very conservative models used to represent RN release and transport. For example, release from bituminised waste (Gr.3) is assumed to be instantaneous despite analogue evidence of similar archaeological and natural materials which show very low degradation over ky timescales. Here it has to be acknowledged that examples under hyperalkaline conditions are limited, but there are certainly arguments to support very low solute release rates from this material, which could considerably constrain concerns about the impacts of resultant high nitrate plumes.

(c) Synthesis

Overall, natural analogues support the main conclusions of the high isolation potential of a robust system of engineered barriers located in a suitable deep geological setting in Japan. However, these analogues highlight limitations in the models used – in particular in terms of overly simplistic hydrogeology and assumption of thermodynamic equilibrium. While the models tend to be very conservative, lack of realism will limit their application to compare different sites and associated repository concepts, as will be needed as the NUMO programme advances. Development of better models will also require appropriate analogues to test them, which is noted as a future goal – particularly for coastal/sub-sea siting options where the analogue knowledge base is particularly limited.

(iii) Supporting arguments by comparison with other safety cases

The work involved in post-closure safety assessment is particularly complex, making it difficult to ensure that all model development and implementation is performed properly and hence that the resulting calculated doses are reliable. One useful check of credibility of output involves comparing different safety assessments with each other [53] [54]. This method provides a holistic overview, providing confidence when any differences in the safety assessment results compared can be explained by variations in the approach, design and geological environment assumed, together with the scenarios assessed and the models/data sets used. However, since the objectives and other conditions vary significantly between safety cases, a strict comparison is not trivial and efforts on such work has only been initiated recently.

Regarding the safety assessment results of this report, examination has begun by comparing with relevant safety cases produced in other countries [55]. Detailed output from the assessments of the three representative host rocks (Supporting Report 6-24, 6-25, 6-26) have also been compared to those of the earlier H12 and TRU-2 studies. For example, the plutonic rock H12 EBS specifications are similar to H12V in this report but, for the H12 reference case, which is equivalent to the base scenario here, the nuclide that contributes the maximum dose is Cs-135 [3] while this report calculates doses dominated by Se-79 (Figure 6.4-23). The reason for this difference is the higher Se-79 solubility in this report while sorption of Cs-135 on buffer material and host rock is larger, giving significant delay and dispersion over the long transport path assumed (see Supporting Report 6-24). Further, the biosphere assessment in this report, assumes a river flow rate 10 times higher than that in the H12 report (based on the latest statistical data, see Section 6.4.1 (6) (ii)), which reduces all doses, although the impact on maximum dose is limited compared to the factors previously noted.

(iv) Synthesis of additional arguments in support of the safety case

In addition to the results of safety assessment, there are several additional supporting arguments that can, or will eventually, support the safety of geological disposal in Japan. Among the approaches to such arguments so far proposed, the safety case developed in this report has considered supplementary safety/ performance indicators, natural analogues and inter-comparison with other safety cases. The purpose, conditions, and applicability of these multiple lines of arguments are briefly summarised in the following.

Different supplementary safety/performance indicators have been applied based on the base scenario and associated models and data, which generally demonstrate the large containment safety function provided by the engineered barriers and near-field host rock for the three SDM cases. Assessing the distribution of total radioactivity with time within the repository system illustrates the great conservatism which has been included in these models and data. The robustness of the containment functions should be further evaluated by applying more realistic modelling and dataset. Also, assessing the distribution of radiotoxicity and the potential radiotoxicity of releases into the biosphere is considered to be useful, but should be carefully applied by taking into account much greater uncertainties associated with the biosphere characteristics and evolution. More realistic biosphere modelling can be developed at a specific site, which can then increase reliability of the application of such an indicator.

While the application of natural analogues strongly depends on the geological environments and repository design, it is useful even for the safety case at this generic stage. However, a careful discussion of the applicability and identifying limitations is needed to clarify what message can be transferred. For example, the analogues applied in this report for geological stability and favourable conditions in Japan only support the claim that appropriate sites could be selected, not that the selected sites can be assured to be favourable. Natural analogues for the engineered system are useful to promote understanding of system behaviour and relevant processes and indicate that present assessment models and data could be overly conservative, which can help prioritisation of further development of more realistic models and datasets.

Inter-comparison of different safety cases is also a very useful tool to increase confidence in the reliability of each element of the assessment basis and the process of integrating these into a safety case, based on analysing the reasons for the similarities and differences between then, see e.g. [54]. Application of the approach for the safety case in this report is limited mainly to the H12 and TRU-2 studies, but illustrates the QA process to check all safety assessment elements and their relationships. Further efforts here will be made in the future, as outlined in Section 7.3.3 (4).

Multiple lines of argument are very useful to support the safety assessment results and strengthen the demonstration of safety, but their applicability and limitations need to be carefully acknowledged. The arguments applied in this report support safety discussions in a generic sense. How these arguments can be used to support the claim of safety for a site-specific repository system is not yet rigorously analysed. At the site-specific stages, however, the application of the supporting arguments will be refined, taking siting environments and tailored repository designs into account.

7.2.3 Constraints on, and scope of, the safety case presented in this report

At the present stage of NUMO`s programme, the safety case developed is inherently limited by the lack of a site-specific context, uncertain boundary conditions and the simplified assumptions, models and databases used for quantitative assessment. This section describes how the current safety assessment allows NUMO to focus and prioritise efforts to develop the refined safety cases needed for future project milestones.

(1) Assuring safety and practicality of geological disposal in Japan

NUMO has established a methodology for selecting favourable geological environments and developing site descriptive models (SDMs) for a range of potential host rocks, an approach for designing a repository with the required safety features for such SDMs that is consistent with the current technological state-of-the-art, and methodology, tools and data that form a sound basis for assessment of the safety of such repository designs. These have been integrated into the current safety case, which provides the knowledge base required in order to proceed with siting after the LS commences in volunteer communities.

The safety case developed in this report cannot be applied to specific sites, but illustrates the fundamental feasibility of demonstrating safety for designs tailored to representative siting environments. In order to move further, specific developments that have been prioritised include:

- Development of a more realistic inventory database that covers all important waste characteristics, based on a bounding range of waste production scenarios. This requires interaction with all those responsible for waste production, conditioning, packaging, storage and transport.
- For TRU waste, the safety case has shown that this can dominate total releases from a combined repository. This justifies reassessment of the EBS and developing more realistic models/databases to quantify its performance in order to increase safety margins. This will require further accumulation of knowledge on identified issues for this waste, such as the effects of nitrates, organic substances, gas generation, and highly alkaline solutions on the safety functions of both engineered and natural barriers.

- Expansion of the assessment base to allow better assessment of coastal/subsea disposal options. A priority is investigation technology to determine geological stability, such as quantifying uplift/erosion and determining the existence of magma chambers and deep hydrothermal fluids. This will be complemented by improvement of the knowledge base supporting development of base and variant scenarios quantifying long-term impacts, including evolution of the EBS and RN release and transport in a saline or mixed/varying freshwater/saline environment.
- As Pre-Neogene sediments represent a poorly studied geological setting, these will be a focus for systematic improvement of the knowledge base, with emphasis on features noted to impact the safety case – such as the consequences of high carbonate waters, which could also be of relevance for other sedimentary host rocks.
- The approach and methodology for a more consistent and coherent safety case that integrates pre- and post- closure phases, taking into account both the perturbation from repository construction and operation activities on the original geological environment, and also THMC evolution of the EBS and near-field host rock during the operational period. This will provide more realistic initial conditions for the post-closure evolution of the repository system required for safety assessment. In addition, it will be important to develop an associated monitoring system/strategy in order to establish baseline conditions before any site perturbations occur.

(2) Applicability as a safety case template

The three SDMs developed are likely to reasonably represent volunteer sites, subject to the constraints noted above. Thus, much of the structure and technical content developed may be directly taken over for the next safety case, after LS to support PI site selection and planning. Nevertheless, problems encountered during the production of this safety case provide guidelines for essential improvements that should be implemented to facilitate updating and restructuring for specific sites. In particular, as noted in the JAEA H17 project, integration and synthesis of the large, multidisciplinary knowledge base that supports the safety case is challenging, with conventional approaches, such as those used in the H12 and TRU-2 reports, now being more difficult, and hence utilisation of more advanced KM tools is identified as a key requirement – possibly more like that illustrated in JAEA's H22 and H26 projects (discussed further in Section 7.3.3 below).

A related challenge was technical QA, which was complicated by parallel work being carried out by different teams on different chapters and their associated SRs. Even though both internal and external technical reviews were carried out, these resulted in many different versions of text components that were difficult to integrate – especially as the documentation software used was very limited in its capacity to support change management. This is again an area where improvement could be built into the safety case template (see also Section 7.3.2 below).

Following the discussion in Section 7.3 on confidence building for the safety case in this report, future perspectives for the application of the safety case as a template are presented in Section 7.4.

7.3 Assuring the safety case is "fit for purpose" (confidence building)

In addition to the issues noted above, development of the safety case after sites are identified will have to incorporate flexibility to respond to site-specific environmental conditions and adapt to both future advances in science and technology and changes in social conditions over the extremely long implementation period (in the order of a century). These are almost unique boundary conditions for any technological project, but adoption and modification of the management framework utilised for this safety case (shown in Figure 1.4-2) can provide a structure for addressing such issues. The goal is thus to assure that, for all programme milestones, decisions can be supported by a safety case that is fit for purpose, contributing to building confidence in the credibility of the repository project.

Thus, Section 7.3.1 assesses the requirements for development of the safety assessment basis, Section 7.3.2 discusses properly handling limits of scientific and technological knowledge and other uncertainties associated with long term predictions, while Section 7.3.3 considers the management aspect of actually implementing such an ambitious goal. Based on this, Section 7.3.4 summarises the confidence that such goals can be met, based on the experience of production of the safety case documented in this report.

7.3.1 Technical basis for Assessment

(1) Ensuring technical quality

In the preparation of this report, a quality management system established within NUMO was applied, which complies to the ISO 9001 standard. It was, recognised, however, that such a general management standard is necessary but not sufficient due to the special challenge of assuring technical quality of the complex, multidisciplinary work involved, especially in the light of the particular problems of documentation under time pressure with limited manpower resources (discussed in Section 7.2.3 above). Here advanced tools to facilitate strict review and associated issues resolution will be implemented in the future.

Clearly, the reliability of the assessment basis, for all components of site characterisation, repository design and safety assessment, depends on the application of scientific understanding based on the latest knowledge. Here, technical quality is assured by conventional approaches: including peer review of concepts, data and assumptions; testing of implementation structures and processes; and verification/validation of models and databases.

The Supporting Reports for Chapters 3 to 6 present the detailed scientific and technical knowledge supporting the safety case, in many cases with information to support its quality - such as publications in peer-reviewed scientific literature. For the mathematical models and calculation codes, in particular, track records of applications and documented verification and validation are reported. For the integrated processes included in the safety assessment, input data for each analysis and resultant output results are stored together in a structured database, together with the concepts and assumptions used to set analysis conditions, to ensure the traceability and transparency of the process. Additionally, as noted in Section 7.2, credibility of output is checked by comparisons with similar cases included in the H12 and TRU-2 reports.

At a more strategic level, the technical basis of this report was reviewed during production by domestic and international experts in the Technical Advisory Committee (TAC) established by NUMO. In addition, objective assessment by the Technology Development

Evaluation Committee, which consists of outside experts, also plays an important role in ensuring technical quality and continuous improvement. The history of such external support is summarised in Supporting Report 7-6.

As described further below, contributions to general quality management result from collaborations with both Japanese and international partners, particularly involving field work and projects in URLs (Section 7.3.3 (3)), where practical experience is gained that will be invaluable when work progresses to the PI stage and beyond. Nevertheless, it is recognised that technical QA is one of the biggest challenges for implementation of a safe repository project and the need for continuous improvement, using BAT, is a primary goal.

(2) Major advances since the H12 and TRU-2 projects

The H12 and TRU-2 projects, completed more than a decade ago, demonstrated that safe disposal of HLW and TRU waste is feasible in Japan. However, when NUMO embarked on the volunteer approach for site selection after the publication of these studies, it was realised that this would require a capacity to characterise and assess sites with quite different levels of geological complexity and also that novel repository concepts might be needed for some of the potential sites. Furthermore, there has been a need to shift focus from research on feasibility to preparing for actual site characterisation, site selection, repository design and implementation. Meeting these challenges has been a focus of NUMO's programme supported by, and closely linked to, R&D carried out by other organisations in Japan, such as JAEA and CRIEPI. Thus, a synthesis of all key developments in Japan which can provide support for increasing the confidence of the safety case is presented below.

(i) Geological knowledge base

Since the start of NUMO's programme, there has been a significant expansion of the geological knowledge base, in preparation for the coming steps in the siting process. It is acknowledged that the siting process requires NUMO to be prepared for very different siting environments and this has been a key aspect of such activities.

A deep understanding of the detailed characteristics of some geological formations that could be potential host rocks has been developed through the work carried out at the two URLs in Japan and through collaborative work in overseas facilities. Crystalline and sedimentary systems constitute a large portion of Japan's geological environment and have been studied at the Mizunami and Honorobe URLs, respectively. The research at these URLs has allowed studies of these rock types at potential repository depth, demonstrated techniques for detailed characterisation and allowed for various tests and experiments, such as studying the evolution of the EBS and other properties over relatively long times, in addition to accumulating more general knowledge on how to construct and develop a repository. Furthermore, NUMO and associated research organisations in Japan have conducted collaborative projects in overseas facilities, thereby expanding knowledge on differences between, not only rock types, but also associated underground conditions that may be encountered at sites.

A nationwide-scale geological database has been developed and will form the basis for the upcoming LS, which will gradually be expanded as more volunteer sites come forward. Using this database, existing data, representing the three different geological settings in Japan that might be suitable for a repository, have been assessed and synthesised into SDMs. In turn these SDMs will be used as input for developing site specific repository designs and associated safety assessment (see Chapter 3).

The geological environmental characteristics used to construct these SDMs were derived from this nationwide scale geodatabase and do not specify a region, with the exception of data obtained from the JAEA URLs. Nevertheless, the development of the SDMs demonstrates how geological information should be handled in a quality-controlled manner and be reflected in the SDM. In particular, the expansion of information on the spatial distribution of rock structural features and groundwater composition, which are important for repository performance, contributes to development of more practical repository designs and more realistic safety assessment. In addition, it is illustrated how sediments of different ages (Neogene and Pre-Neogene) can significantly differ in key mechanical characteristics, which are important for the design of repository, and the structure of flow paths, which are important for safety. This is captured in the SDMs developed for these potential host rocks. It was noted that information on the geological environment for Pre-Neogene sediments are relatively limited compared to the other two potential host rocks examined.

Apart from advancing the specific knowledge of these geological settings, the SDM methodology will be a key tool for synthesising data from other geological settings that may result from the siting process. Furthermore, NUMO also continues developing the SDM methodology, including how to assess and incorporate time variation, such as sea-level change, uplift and erosion or tectonic evolution.

Finally, an approach for handling the tectonic hazard, which could potentially be an issue at some sites, has been developed. NUMO has also conducted an international project [56] on how to assess, and mitigate, risks from the tectonic perturbations that potentially would be an issue at some sites.

(ii) Engineering knowledge base

A requirements-driven design process, outlined in Chapter 4, has been established. This process will meet the needs of an implementing organisation to consider a wide range of requirements, including practicality of construction and operational safety, to adapt and optimise designs during the different steps of the siting process and to develop repository concepts for novel siting environments.

To date, assessment and further development of the H12 and TRU-2 concepts have been a focus, in particular for consideration of practical construction and operational safety. This led to an alternative H12 design that utilises a PEM, in order to meet potential challenges during waste package emplacement. Alternatives for overpack design, material and welding have also been assessed. Regarding TRU waste, a waste package design that will be more robust during the operational period has been studied, as well as alternatives for emplacement and backfilling the waste. This report also focuses on the co-disposal option, taking into account interactions between the HLW and TRU repositories. Finally, it has been demonstrated how to adapt repository layouts for these concepts for the three different siting environments assessed.

As discussed in Chapter 2, it is inevitable that large uncertainties will exist at early stages of the stepwise implementation programme and hence there is a need for the programme to be sufficiently flexible, i.e. to have the capacity to deal with changed conditions and to evolve towards implementation and eventual final closure accepted by all stakeholders [57]. This can be achieved by identifying the most significant uncertainties and focusing R&D to either reduce uncertainty directly, or the impacts of this on repository performance. At the current stage of the siting process, there is a need for developing robust repository concepts to reduce impacts of safety case uncertainties. Furthermore, and especially since sites with properties deviating from the three studied environments could emerge, there might also be a need to develop novel repository concepts for such environments, as further discussed in Section 7.4.

A process for adapting repository design and layout to the specific geological conditions has been demonstrated. In addition to the basic requirement of excluding active faults from the repository area, a more elaborate assessment is presented that assesses what to avoid, depending on the scale of any faults or similar structural features present. Criteria on where waste and buffer materials can and cannot be placed (see Section 4.5.4) are presented. For example, it is assumed that, for faults with a length of 1 km or more, the width of the damaged zone surrounding the fault is about 1% of the fault length [5] and consequently emplacement within this zone should be avoided. However, as there is likely to be uncertainty in the position of the fault, emplacement close to the damaged zone boundary should also be avoided. Furthermore, waste emplacement locations need to consider operational factors such as waste transportation, appropriate drainage and ventilation systems, etc.

In this way, repository layout is adapted to characteristics such as the three-dimensional distribution of faults, fractures and permeability represented in the SDM and this can be reflected in the RN migration analysis model for safety assessment. This process will thereby allow feedback from the safety assessment, both to site characterisation and formulation of criteria used in design work.

Engineered barrier designs have been improved and judged more reliable, reflecting new test results on overpack corrosion and the swelling of buffer material (see Section 4.4). In addition, as preparation for flexibly responding to various site environmental conditions, development of different design options was carried out (see Section 4.5.4). For example, for HLW repositories, the introduction of a PEM for horizontal emplacement in a deposition tunnel is judged to simplify the emplacement operation and quality control of the buffer, and to make it much less sensitive to ingress of groundwater during operation and re-saturation compared to the vertical emplacement option using unprotected bentonite buffer blocks. Layout, workability, operability and compatibility with the geological environment for dead-end versus open-ended deposition tunnels have also been assessed.

Regarding TRU waste, an alternative waste package container with a lid allowing lifting from the top has been introduced to improve both handling and safety during normal operations and also reduce vulnerability to abnormal states, such as dropping of waste.

Engineering technology has also developed in areas such as overpack welding, non-destructive testing and buffer manufacturing / installation (block method, in-situ compaction method, pellet filling method, etc.). The applicability of some of these technologies has been confirmed by empirical studies at full-scale (see Sections 4.4.1 and 4.4.2). Several full-scale demonstration tests on waste deposition technology, grouting technology, tunnel plug construction technology, etc. have been conducted (in domestic and overseas URLs), demonstrating their technical reliability. Furthermore, basic R&D has shown the basic feasibility of the technology that supports retrievability of already emplaced waste, as specified in the Final Disposal Policy.

Finally, focus on actual project implementation is a key aspect of the design work. For example, regarding operational safety, safety measures for both above and below ground facilities that refer to the regulatory standards for nuclear facilities (reviewed after the Fukushima Daiichi Nuclear Power Station accident) were specifically examined. This means that, for the operational phase, there is a need to look at low probability events if they are likely to have large consequences. For underground facilities, in addition to nuclear safety, key issues concern construction, ventilation, drainage and worker safety.

(iii) Safety assessment knowledge base

The safety case presented in this report demonstrates the use of several approaches and methodologies that will allow it to identify further development needs and eventually be the basis for site selection and licensing of a repository. More specifically, the following can be noted:

- A fault tree approach is included for scenario development during the operational phase.
- A formal process for identifying and developing post-closure scenarios using a storyboard approach is developed and applied.
- There has been a move towards increased realism and less conservatism, but, as noted in Section 7.3.2, further developments in this direction are needed.
- A more systematic and well-documented process for setting key parameters of RNs migration is adopted.

These points are further elaborated in the following subsections.

(a) Safety measures and safety assessment before closure

Regarding safety before the closure of the repository, the regulatory standards for nuclear facilities were reviewed after the accident at the Fukushima Daiichi Nuclear Power Station and the implications for how to assess operational safety has also considered experience in other countries where repository projects are in, or nearing, the implementation stage. This forms the basis for developing the more systematic and quantitative methodology for operational safety assessment presented in this report.

An event tree approach is established to identify and evaluate scenarios that describe the transition to abnormal or potentially detrimental conditions that could occur in the repository. In addition, by creating and continuously expanding a database of such events in relevant industries, it has become possible to ensure the traceability and completeness of the scenario development process.

Using this technique, several potentially detrimental scenarios have been identified and assessed, including waste drop, fire, and loss of power. The probability of these events and the ability of the waste and waste packages to retain their containment properties have been assessed. Also examined were countermeasures in the unlikely event of an accident. It is concluded that, with the right procedures and countermeasure in place, the occurrence and consequences of assessed events are low and radiological impacts on workers or the public are very unlikely

(b) Assessment methodology for post closure safety

Currently, a risk-informed approach to assessing long-term radiological impacts is adopted, based on the dose calculated for specific scenarios and the probability of these occurring. To initiate this approach, systematic methods for developing scenarios belonging to each category were used. After formally describing the behaviour of the geological disposal system after closure, facilitated by the use of storyboards, a top-down method of considering the safety functions expected for the components of the repository system was combined with a bottom-up approach based on assessment of relevant FEPs. Such FEPs are compiled from the latest internationally developed databases and the FEP lists used in previous Japanese safety assessment to ensure that the resulting list (NUMO FEP list) is comprehensive.

In developing the models and setting up the data sets for scenario consequence analysis, consideration was given to realistically reflecting the characteristics of both the SDM and repository to the extent possible. Specifically, a three-dimensional model was utilised to explicitly evaluate the arrangement of components of the repository with respect to features in which groundwater flows and RNs migrate within a limited portion of the surrounding host rock. However, it is admitted that the scenario selection will need to be updated in Safety Cases for specific sites and that the current groundwater and RN modelling approach is simplistic and does not fully take into account the three-dimensional aspects of the entire repository in its setting within the SDM. As is elaborated upon in Section 7.3.2, further developments in this direction is needed.

(iv) Progress in knowledge integration

Compiling and integrating geology, engineering and safety assessment knowledge within a coherent safety case is a key challenge. This has forced geoscientists, designers and safety assessors in the programme to interact and provide feedback on development needs across a range of different disciplines. Developing a comprehensive SDM as demonstrated in Chapter 3, using this for developing site-adapted designs (Chapter 4) and deriving associated safety assessment calculation cases (Chapters 5 and 6) are critical steps in this process. In addition, this work also provides the framework for the feedback loop where safety assessment should guide further site characterisation and repository design work.

Assessing co-disposal of HLW and TRU waste is another area of knowledge integration. This forces consideration of how evolutionary processes for TRU waste, such as the effect of nitrate contained in Gr.3, would affect migration from the HLW part of the repository.

Using storyboards to visualise the temporal evolution of repository safety functions, as demonstrated in Section 6.3.1, facilitates understanding of the behaviour of the repository system and improves dialogue between experts in different fields. This approach will also ensure consistency and traceability from scenario creation to formulating the corresponding analysis cases, based on the understanding of the SDM and the related repository design. However, it is recognised that storyboards alone may not suffice to develop a comprehensive set of scenarios, especially since the different evolutions expressed may not be independent. Further developments to improve this situation are thus planned.

7.3.2 Dealing with uncertainty in the safety case

When creating a safety case, it is necessary to take careful measures to deal with uncertainties associated with the limits of scientific and technical knowledge and the resulting constraints on predictions of future evolution. Uncertainties originate from lack of system understanding as reflected in the assessment basis, i.e. the site descriptive model, repository design and approaches for safety assessment. Key uncertainties that are due to lack of knowledge and those due to inherent variability need to be distinguished and the impacts of these understood.

As will be further outlined in the following subsections, this safety case has highlighted many important uncertainties. This will form the basis for uncertainty management, such that their impacts can be reduced in a structured manner as siting proceeds. However, as is also pointed out in several places throughout the report, progress here has been limited. Instead, uncertainties are often handled by simplifying descriptions, making conservative assumptions and introducing stylisations. This approach is justified at present, since data from specific sites are not yet available and detailed designs for these remain to be developed. However, this also means that, at this stage, only limited conclusions can be drawn on key issues, like differences between sites, waste packages or layouts. In coming steps, it will be essential to introduce much more realism in all components of the safety case and to quantify the associated uncertainties. This will be a key goal for the future.

(1) Dealing with uncertainties related to the assessment basis

(i) Uncertainty in the site descriptive model

As mentioned in Section 2.5.1, uncertainties related to the investigation and evaluation of the temporal and spatial characteristics of geological environment include measurement errors, measurement constraints (spatial resolution, measurement density, etc.) and lack of data. There are also uncertainties in the characterisation data due inherent heterogeneities, limitation of associated interpretation and the resulting conceptualisation of the geological environment. Since these uncertainties depend on the geological conditions of the site and the measurement methods applied, it is impossible to quantify all of these at this stage. When constructing the SDMs presented in this report, the distribution and trends of numerical data such as mechanical, hydraulic, and thermal characteristics are based on data collected on a nationwide scale. Representative characteristic values are set for each host rock to be examined, but uncertainty is not directly treated. These uncertainties will be considered when developing the SDMs during the actual site characterisation stages, taking into consideration the technology applied and the geological setting of the actual site.

In addition, as mentioned above (Section 7.2.1), the current SDMs do not reflect the temporal changes in topography or characteristics of geological structures. In the future, as described in Section 3.5.2, the construction of a 4D SDM will capture temporal evolution with its associated uncertainties.

The characteristics of faults and fractures have a great influence on the extent of RN migration. The inherent variability in parameters such as the hydraulic conductivity of the rock matrix and preferential flow structures such as faults and fractures are represented as probability distributions. Currently, large faults are represented by an average permeability. In the coming characterisation of actual sites, the positions and orientations of large-scale faults and active faults with lengths of $>\approx 10$ km will be described deterministically, since these features need to be excluded from the repository area. Smaller faults and fractures will be treated stochastically, based on assessed distributions of their characteristics. In safety assessment, associated uncertainty will be handled by generating and analysing different realisations based on the distributions, thus capturing the impacts of heterogeneity of these features. These uncertainties will, however, be reduced as the characterisation database expands.

(ii) Uncertainties in the repository design and engineering

In the design of the repository, the uncertainty included in the SDM is taken into consideration to some extent. Specifications have been set with margins for engineered barriers and underground facilities to ensure that expected safety functions are not compromised for a wide range of host rock properties. For example, in the design of engineered barriers (see Section 4.4), the specification of the overpack is set to ensure that it will remain tight for at least 1 ky after repository closure for all three host rocks examined. Indeed, this safety margin results in a design that would likely maintain the safety function of suppressing contact between vitrified waste and groundwater well in excess of 10 ky based on a more realistic assessment. In addition, the mechanical effects of various phenomena, such as repeated seismic motions , corrosion expansion of metals, chemical alteration of buffer, and creep deformation of bedrock and buffer materials, are currently evaluated with conservatively set parameters that may have greatly exaggerated potential effects on the safety functions. Therefore, depending on the conditions of the geological environment, the currently applied margins and criteria should be revisited.

In addition, before sites have been specified, it is necessary to prepare for uncertainties in both site environmental conditions and socio-economic requirements. For this reason, as described in Section 4.8.3, consideration of tailoring is based on multiple requirements, including safety and engineering practicality for different geological and environmental conditions, ease of material procurement, and economics / environmental impacts. At the same time, alternative materials for engineered barriers and further design options are being developed. Advancing the capabilities of technology for evaluating the long-term behaviour of the EBS and assessing the uncertainties related to quality during manufacturing and construction of engineered barriers, will be important in order to reduce uncertainty related to quantifying long-term EBS performance. Further work on confirming the applicability of engineering technology through demonstration tests will be carried out in order to examine measures to reduce current safety margins based on reduction of some uncertainties associated with repository design.

(iii) Uncertainty associated with safety assessment

In the pre-closure safety assessment, abnormal state scenarios in which safety measures do not function normally are developed. Efforts are being made to improve the evaluations of such scenarios within an international project on the operational safety of geological disposal [58], which may reduce associated uncertainties.

The range of knowledge and data available on post-closure behaviour of the repository is considered sufficient for the current stage of assessment. In consideration of known uncertainties, the evaluation is divided into base scenarios, variant scenarios and low probability perturbation scenarios. At present, safety evaluation is performed to confirm feasibility of safety demonstration, taking a conservative approach and intentionally using models and data that overestimate consequences. This applies not only to the variant scenarios, but also to the analysis cases for the base scenarios. Additionally, not only a dose constraint value (300 μSv/y) consistent with recommendations by international organisations is considered, but also the strictest limit from safety regulations of other countries is set as a target value for the base scenario (10 μSv/y). Further, within safety assessment scenarios, FEPs in the NUMO list considered to have a favourable effect on safety are not included if there are no reliable data or models to quantify them (often termed reserve FEPs, see Section 6.3.2 (3)).

In the modelling, the focus was on the containment performance of the repository, and it is assumed that RNs that migrate from the repository scale area (several km x several km) directly enter the biosphere for dose calculation purposes (see Section 6.4.1 (5)). As a result, the evaluation is conservative with regard to the safety functions of RN sorption and migration in the large volume of rock between the repository and the biosphere.

For the RN migration parameters, as described in Section 6.4.2, conservative values for solubility and sorption coefficients are selected. In addition, a sensitivity analysis is performed by considering a wider range of migration parameter values. Apart from cases with unrealistic combinations of parameter values, none of the results exceeded 300 μSv/y.

Low probability perturbation scenarios and human intrusion scenarios are, in accordance with international practices, handled by a stylised approach. Some parameter values used are also conservatively set so that the effects of these phenomena are overestimated (see Sections 6.4.3 and 6.5). However, even if such a stylised approach implies that detailed site-specific analyses may not be needed, current assumptions are possibly oversimplified and will be revised in coming assessments.

In both the process evaluations and RN migration analyses carried out in this report, limitations in computational capacity restricted models of some of the phenomena occurring in the disposal system and on the scale of RN migration considered. In addition, the migration data is constrained by the limited range of information in the existing database. For example, U-233 migration data in groundwater with a high carbonate concentration does not exist at present. Such limitations are handled by a conservative approach, i.e. by discarding sorption both in the near- and far-fields in cases where there are no reliable data.

As further discussed in Section 6.6.2, several actions are planned to further improve the technical basis for safety assessment and carry out sensitivity analyses to identify and reduce key uncertainties. This includes the following initiatives:

1. Make assessments more realistic and to account for all components of the repository system in their specific geological settings. In particular, more realistic RN release and migration models for both the EBS and geosphere should better reflect the three-dimensional characteristics of both for specific sites and the repository concepts tailored to them, in line with the stepwise improvement of the knowledge base. In addition, more emphasis on model testing, verification and validation will be needed in later stages of this process. However, when uncertainties are large and difficult to quantify, conservative assumptions will also be needed in the future.

2. In order to improve traceability, the components within the workflow, from development of scenarios to setting of analysis cases based on the understanding of the behaviour the repository system, will be formulated in a more systematic way, utilising advanced knowledge management tools.

3. In terms of such technology development, focus will be on the actual volunteer sites in order to ensure that more reliable assessment of safety functions of repositories tailored to them can effectively contribute to the comparison between sites and the optimisation of repository designs for these.

4. Continual expansion of the RN release and migration database for relevant geological environments and associated evolution of the EBS for the wastes considered.

(2) Confidence in dealing with uncertainty

In the post-closure safety evaluation of this report, as mentioned above, it is essential to ensure confidence in the process of integrating individual evaluations based on the knowledge available at this stage. Thus, safety is also assessed using complementary indicators (other than dose) that are not affected by uncertainties regarding future human lifestyles, surface environment conditions or the long-term geological stability assumed in the main analysis. In this way, credibility of conclusions is built even in the light of such uncertainties.

Information on uncertainties related to site characterisation and modelling should be integrated into the SDM and reflected in repository design and safety evaluation. Users then provide feedback on how to focus further characterisation work. Based on this safety case, some factors related to the geological environment were identified that could have a significant impact on engineering practicality and safety of the repository, and uncertainties associated with these could be reduced when setting targets and their priorities for coming site characterisation stages will be clarified. Using safety sensitivity analyses to focus site characterisation and design work will continue and be further developed as the programme moves forward.

Once characterisation efforts are started for a specific site, the understanding of the geological environment will be enhanced and factors that are highly relevant to uncertainty (for example, spatial distribution of faults and hydrological characteristics) will be assessed and better described in the SDM, thereby reducing uncertainty. At the same time, cooperation and iterations between the site characterisation, repository design and safety assessment teams should be more focused in the future.

In order to facilitate integration and cooperation, changes in geology and various other conditions that may be expected over the long project period should be considered when creating a safety case. Thus, Section 7.3.3 presents a management framework and method of responding to uncertainty related to development of the SDM, the design of the repository, and the safety assessment which will increase confidence in the overall project.

7.3.3 Structured management of safety case development

(1) R&D management

In order to constantly improve safety cases, it is necessary to clarify key open issues and establish a R&D framework to resolve these. In Japan, this framework has already been established and will undergo continuous review to assure that it meets NUMO’s (and other stakeholders’) requirements.

As mentioned in Section 2.5.5, the Coordination Council on R&D of Geological Disposal, consisting of METI, NUMO and related research institutes, has been established to provide the framework for tackling R&D issues related to geological disposal. Goals and priorities are agreed and set out in an Overall R&D Plan [59], which is reviewed as appropriate in order to reflect the progress of science and technology, changes in requirements, and the R&D results obtained.

In line with the overall plan, NUMO compiles a medium-term technology development plan every five years, with a clear division of roles between basic R&D institutions. This explicitly identifies progress required for the safety cases needed for future milestones, with a current focus on planning PI and integrating output as a basis for site selection [60]. At a strategic level, key components of this plan are regularly reviewed by Japanese and international experts in NUMO’s Technical Advisory Committee (TAC). This role was previously covered by separate ITAC (International Technical Advisory Committee) and DTAC (Domestic Technical Advisory Committee), but integration was implemented to improve both efficiency and development of common domestic/international perspectives.

Assurance that the output of R&D is of sufficient quality and is representative of the state-of-the art is provided by regular publication in scientific journals and presentations at national and international conferences, together with focused national/international review workshops on key topics.

(2) Promotion of R&D cooperation

In order to effectively promote technological development, NUMO participates in joint research with related organisations in Japan and in collaborative projects with international partners. This facilitates capture of both tacit and explicit knowledge and access to infrastructure that NUMO does not possess, particularly conventional laboratories, test facilities and URLs.

Such research cooperation is internationally recognised to contribute greatly to the development and implementation of geological disposal projects (e.g., OECD/NEA [61]), resulting in a wide range of initiatives coordinated and/or funded by the IAEA, NEA, EU and similar organisations. NUMO and supporting R&D organisations actively participate in many such joint international projects, but also collaborate with partner implementers in bilateral or multilateral R&D projects [62]. In addition to input received, NUMO will actively contribute by sharing the results of technological development in Japan and also the experience gained in creating safety cases at various international cooperation forums.

Research cooperation is also beneficial for human resource development (see (5) below), and mid-level or higher-level staff are involved in overseas projects in order to maintain and extend the international level of technology. At the same time as solving problems, NUMO is trying to improve technical capabilities by participating in an international network of experts. A cooperative framework for young staff members has been established, so that they can experience relevant work from test planning to test implementation and data acquisition, and thus develop as the key scientists and engineers who will carry NUMO forward in the future.

In the future, topics that may be ideal for collaboration due to common interests with some international partners will be examined – such as designing and assessing safety of coastal repositories, repository design optimisation, and developing new analogues to test key areas of safety cases (e.g., RN release and transport). Here, NUMO would expect to play more of a lead role than has been the case in the past.

(3) Structured response to changing boundary conditions

It is understood that the boundary conditions for the safety case will change with time and as the siting programme proceeds. Such changes need to be managed in a structured way.

As the nuclear power programme in Japan evolves, this will affect both the volumes and types of nuclear waste that will eventually need to be disposed of. This may primarily affect the siting programme, as a larger disposal area may be needed, and the repository design work, since new designs may be needed to handle other types of waste. However, the general approach in developing SDMs and the requirements-driven design process is judged sufficiently flexible to handle such potential developments.

Nuclear safety regulations may also change, e.g. in the approach to handling risk or to what extent they will be more, or less, prescriptive on specific requirements for sites or engineered barriers. The safety case methodology must be sufficiently flexible to handle such changes. It is judged that NUMO's safety case methodology has this flexibility, since it builds on internationally accepted principles and practices applicable in a very wide range of regulatory environments.

Properties and other conditions at sites that will come forward and then be investigated are largely unknown at present. Surprises may also come later, when detailed underground data become available during the PI and DI stages. Repository designs may need to be revised and the means of assessing the safety relevance of these surprises must be available. The comprehensive SDM methodology and the requirements-driven design process developed and applied are judged capable of providing sufficient resilience, i.e., the capacity to deal with changed conditions and meet associated challenges. Again, the fact that NUMO's safety case methodology is in line with principles and practices applicable in a very wide range of siting environments worldwide adds to this confidence.

As elaborated in Section 4.1, repository design will be optimised in steps starting from a conceptual design, followed by basic design and finally, detailed design that will be tailored to the developing understanding of the siting environment. The word "optimisation" has a special meaning in radiation protection, but needs special consideration for geological repositories[1]. Thus, optimisation in NUMO's programme goes beyond radiological safety and also includes searching for more practical and efficient repository designs, while ensuring the radiological and other environmental impacts are kept sufficiently low. Furthermore, optimisation needs to balancing different, often conflicting, requirements. For example, the development of technologies that support retrievability shown in Section 4.7 is response to uncertain social factors, such as changes in requirements from stakeholders. A holistic approach to optimisation allows parallel consideration of a range of relevant issues, including efficiency, worker safety during repository construction, operational radiological safety, post closure safety, environmental impact and efficient use of natural resources.

Optimisation is related to the concept of BAT, but is not the same thing. In the European Union, BAT means the most effective and advanced stage in the development of activities and their methods of operation. This "indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole" (IED (2010/75/EU) [64]).

Application of BAT, in the context of geological disposal, means that the technology used for siting, design, construction, operation and closure of the repository should be suitable for the overall goal to prevent, limit and delay releases from both engineered and geological barriers as far as is practically possible. Since final designs are not yet selected, BAT can also be seen as an awareness of the current state-of-the-art, to ensure that development is not

[1] For these cases the ICRP [63] states that *the elements guiding or directing the optimisation process should be those that directly or indirectly determine the quality of the components of the facility as built, operated, and closed, where quality refers to the capacity of the components to fulfil the safety functions of containment and isolation in a robust manner. The assessment and judgement of the quality of system components essentially includes the site characteristics, elements of Best Available Technique, as well as the concepts of good practice, sound engineering, and managerial principles*.

frozen and technology is further developed and modifications to concepts and designs introduced as and when appropriate. Once an optimised concept is decided upon, therefore, the best available technology is chosen for its implementation.

Science and technology will advance during the course of the repository project and technological breakthroughs may allow for novel or more optimal designs. To meet these challenges, it is essential that the programme retains and further develops a sufficient scientific and technological competence. Ensuring that there is a comprehensive understanding of the structure and content of the NUMO SC is essential for this. In meeting these challenges NUMO has also started to build a system for systematically managing knowledge and human resources (Sections (4) and (5) below).

(4) Requirements and knowledge management

A safety case requires the compilation, integration and synthesis of a huge volume of diverse, multidisciplinary knowledge in a structured and quality-assured manner. Furthermore, such a knowledge base is expanding at an exponential rate, which can be expected to continue over the duration of the repository project (in the order of a century – or longer if institutional control is considered). It is clear that the traditional knowledge management (KM) approaches used at the time of the H12 and TRU-2 reports are no longer suitable for this task – as well recognised in other fields that handle “big data”. JAEA, as an R&D organisation supporting both geological disposal implementers and regulators, established a project in 2005 to develop improved KM approaches and tools (e.g., [65] [66]). In the development of such an advanced knowledge management system (KMS), both explicit and tacit knowledge were included, with application of cutting-edge information and knowledge engineering tools. The resulting KMS was focused on safety case development and its effectiveness demonstrated in the H22 project, made available on the “CoolRep” web-based communication platform (e.g., [67] [68]).

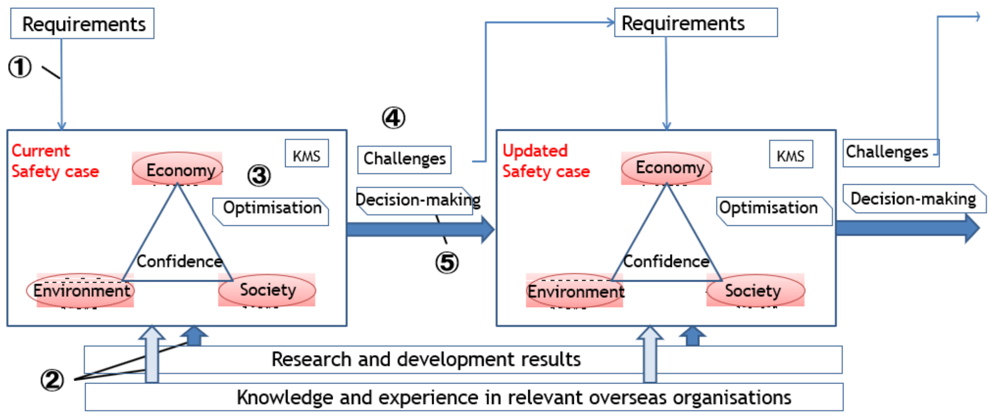
International guidance on what to include in a safety assessment, e.g. as provided by the OECD/NEA [69], to a large extent originates from intercomparisons between safety assessments developed for a wide range of geological environments, waste inventories and stages of development. Since NUMO’s safety case aims to be consistent with such advice (Section 1.4.2), this provides further confidence in the aim for completeness of the work and is an essential source for enhancing the knowledge base.

However, the information, data and knowledge to be incorporated in a safety assessment is dramatically increasing and hence the intercomparison of different safety assessments is very challenging and requires participation of experts in all the different disciplines contributing to develop a safety case. The inter-comparison of safety assessment is a key area for international collaboration and an advanced knowledge management system can also be of a great help here, providing a common structured framework for all participants.

As mentioned in Sections 2.5.3 and 2.5.4, NUMO is developing systems for both requirements and knowledge management, with emphasis on its roles as a repository implementer [70]. In developing safety cases that evolve but preserve traceability over the long project implementation period, ensuring that decisions are made in an open and transparent manner, it is internationally agreed good practice to introduce a requirements management system (RMS). This integrates constraints set by environmental protection, societal acceptance and economics with the fundamental principles, regulations and guidelines for geological disposal, as suggested by the IAEA [26]. As a result, the RMS facilitates developing solutions that satisfying occasionally conflicting requirements, with appropriate balances and trade-offs explicitly recognised.

There is a clear relationship between the RMS, which defines the decisions to be made, and the KMS, which provides the knowledge to allow decisions to be soundly based – as was recognised during development of the JAEA KMS (e.g., [65] [66]). The NUMO concept for combining requirements and knowledge management within an integrated system is shown in Figure 7.3-1.

The development of such a combined requirements and knowledge management system for geological disposal is included in both the most recent Overall R&D Plan and the NUMO medium-term technology development plan mentioned above. Knowledge management in radioactive waste management is increasingly recognised an important issue, leading to initiatives like the OECD/NEA international project WP-IDKM (Working Party On Information, Data And Knowledge Management [71]) and NUMO will actively participate in such activities to ensure that our developed system is and remains at state-of-the-art levels.



① Analysis of current requirements (e.g. requirements for project and safety regulations, requests from the local community)
② Use of current scientific and technical knowledge
③ Integration of knowledge into the safety case, optimisation in the light of constraints (environmental, social and economic) to ensure project practicality, building stakeholder confidence
④ Identify the problems to be solved in the next stage (identify knowledge needs)
⑤ Based on the credibility of the safety case, remaining challenges and social dialogue, a decision is taken to proceed to the next stage.

Figure 7.3-1 NUMO requirements management concept and its relationship to knowledge management

(5) Human resource management

In order to make geological disposal sustainable for its very long implementation period, required human resources need to be available, with critical tacit knowledge preserved and communicated/transferred across generations. This is highlighted in both the Overall R&D Plan and NUMO 's medium-term technology development plan. Traditionally, an effective approach was for experienced specialists to pass on their experience and know-how to young staff through on-the-job training (OJT).

Such OJT forms a key component of both general R&D and collaborative projects, which is recognised by NUMO. Indeed, this was an explicit aim of the current report, which was produced predominantly by a young team rather than the senior experts responsible for the

H12 and TRU-2 reports. Even if this is not the most efficient way to produce a safety case, the close interaction between the production team and both national and international expert reviewers provided an invaluable opportunity for knowledge transfer.

It is important that human resource development efforts are not limited to NUMO, which is the implementer, but are widely promoted by regulatory agencies, related research institutes, and industry, which are major producers of new knowledge. In response to the Overall R&D Plan, the Ministry of Economy, Trade and Industry (METI), NUMO, and related research institutes are promoting efforts to jointly hold training courses for young staff from both industry and universities.

Tacit knowledge capture is a particularly urgent concern in Japan, due to aging of highly experienced specialists and generalists who have been involved in past geological disposal planning, with a clear risk of loss of institutional knowledge and know-how. It is difficult to capture such experience and know-how and convert it into explicit knowledge, and OJT is a time-consuming process, so this is a priority area for application of tools to support tacit knowledge preservation – for example based on expert systems.

(6) Communication of safety cases to stakeholders

Safety cases provide important background for stakeholders, facilitating their understanding of the key issues associated with geological disposal and encouraging dialogue to ensure their contribution to decision making. In order to perform this role, a safety case must be communicated at technical levels appropriate to the different stakeholder groups. Stakeholder communication is also recognised as a challenge at the international level, for example in the long-running OECD/NEA Forum on Stakeholder Confidence (FSC; established in 2000) [72]. NUMO actively participates in such international activities, with communication of the safety case being promoted as a special area of concern.

This particular report was developed at a technical professional level, aimed in particular at experts in the geological disposal field, and hence is not easy for non-experts to follow. Thus, to respond to the interests of stakeholders and promote communication, it is complemented by a pamphlet explaining the main points that this report aims to present ("The concept of ensuring the safety of geological disposal" [73], in Japanese only). A wider perspective, including more international background, is provided in the report "Why Geological Disposal" [74] (also in Japanese only).

To facilitate accessibility, NUMO has also developed a web system for viewing the entire safety case documentation (currently in Japanese only), making it easy to read or download the report as a whole or as summaries (e.g. Main Report chapters and Supporting Reports). Specifically, the Supporting Reports here are linked directly to chapters that reference them, making it easier to browse specific topics. In addition, wherever possible, references cited in this report are also linked to the main text and can be directly accessed as pdfs (including NUMO technical reports, JAEA research and development reports, and reports of some other supporting organisations). To widen availability, such access is possible not only from personal computers but also from other devices such as tablets. In addition to documentation, more direct presentation of the safety case to various stakeholders by qualified experts is also promoted [75].

Through nationwide communication with stakeholders via interactive briefings [76] and establishment of open and transparent dialogue in volunteers areas where the initial literature search is accepted, NUMO will continue to address any stakeholder concerns related to the safety case and reflect them in future planning. When the programme advances to specific sites, efforts to enhance and widen communication with all stakeholders will progress to ensure that different stakeholders can also be involved in relevant parts of future safety case production.

7.3.4 Acceptance of safety case content

The efforts described above to develop and improve components of the safety case are necessary but not sufficient. In order to assure that a safety case is fit for a specified purpose, it is extremely important to conduct independent reviews of the safety case as a whole. As mentioned in Chapter 1, when preparing this report, NUMO published a Japanese language review version and asked the Atomic Energy Society of Japan (AESJ) to organise such a review by qualified experts who were not directly involved in its preparation. This technical review was then used to make revisions reflected in the present text – which is then assumed as accepted to be fit for its role at this pre-siting stage. NUMO will confirm this by reviews of this English version, in the first instance by our TAC and then by an international organisation such as NEA.

Also, in the future, NUMO will continue to carry out independent safety case reviews by national and international organisations, to ensure that these reflect the progress of science and technology, trends in safety regulations, etc., and thus that these are fit for the specified purposes of the milestones in our evolving programme.

7.4 Outlook for future safety cases

The previous sections outline the benefits and limitations of the present safety case to serve as a technical base for stepwise site investigations, leading to site selection and, eventually, repository implementation. It provides direct input to guide literature searches at volunteer sites, as have recently been initiated in Hokkaido. However extensive development is required to develop the site-specific safety cases that utilise LS information to support selection of PIAs and planning the focused investigations that will be required at each site. This, in turn, will lead to further development needed for future programme milestones, as discussed in more detail below.

7.4.1 Building an evolving safety case

(1) Development of site-specific safety cases

As noted in Section 2.2.3, geological information obtained at each stage of stepwise site investigation provides an evolving basis for repository design and safety evaluation, contributing towards determining the eligibility of a site (or specific areas within it). The safety case and the developed RMS serve a key integration role, assuring safety of construction, operation and after closure, which are the highest level requirements for a potential project, even if these may not be entirely without conflicts that require careful resolution. Site selection will, however, require considerations in addition to safety but, even after a site is selected, the safety case will play a key role in moving towards and eventually applying for construction and operation licenses. Indeed, even after construction is initiated, geological and engineering information obtained will result in continuous updating of the knowledge base supporting the project and the safety case will facilitate optimisation of the implementation plan to take advantage of this. It is also expected that regulations will require regular safety re-evaluations during the operational period, up to a final safety case to support licensing closure of the repository. This is summarised in Figure 7.4-1, which also indicates the changing boundary conditions and constraints over this period.

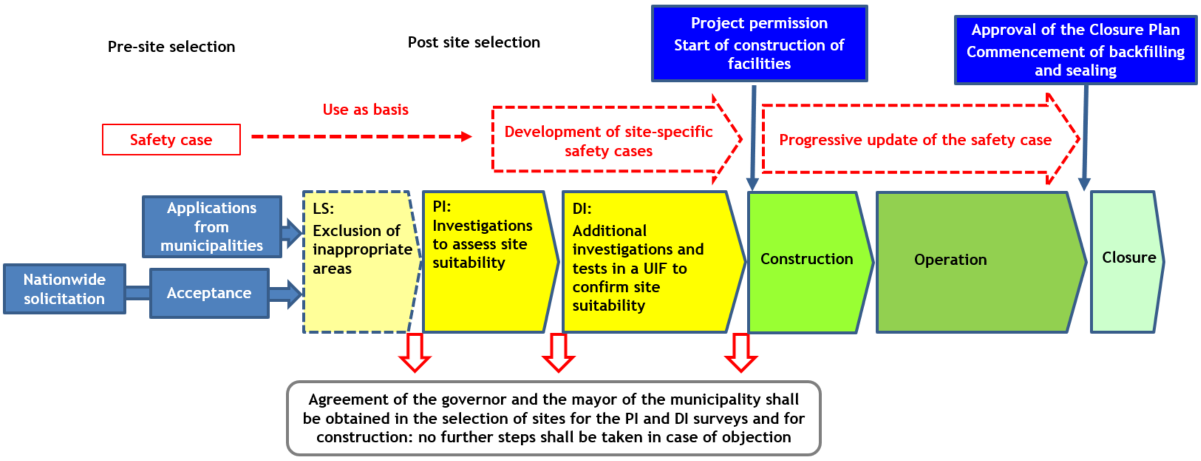


Figure 7.4-1 Concept of stepwise safety case evolution

(2) Tailoring the safety case to stepwise site selection

In the following outline, an idealised process for moving through the siting process is presented, with a focus on the role of the safety case within it. It emphasises assuring flexibility, but it is recognised, based on international experience, that surprises and perturbations may arise that disrupt this process – not only due to the findings during site investigations but also changes of external boundary conditions. Nevertheless, this provides a good basis for planning and will, in the future, be complemented by more detailed risk assessment to determine potential perturbations and strategies to respond to them.

(i) Literature survey stage

At this stage, it is first required to confirm that the legal requirements for an acceptable site are met. From the viewpoint of creating a safety case, the geological information that can be obtained is limited and it is likely that input will include only the extent and location of potential host rock(s) and very general properties of associated geological setting(s). However, in order to prepare for the next siting stage, additional work is needed during LS.

While fulfilling the legal requirements, consent of the local municipality will be required to go forward to the PI stage. It also clear that only sites that fulfil the legal requirements and have reasonable prospects of hosting the repository should be considered for further study. This will be especially important if many different LS sites arise that meet this basic qualification. Planning the site investigations for the PI stage is based on what is obtainable from the LS and identifying the repository concept development needs, with the dual objectives of determining the prospect of the site being suitable and forming the basis for planning effort in case the site is selected to go forward.

Therefore, regarding the production of the safety case, technical improvements will be needed, as discussed in Sections 7.3.3 (1) and (2). In addition to study of the legal requirements, the following will be assessed:

- Arrangement of underground conditions such as distribution of strata, rock formations, faults, etc.
- Examination of which strata are considered to be more preferable.
- Examination of land use restrictions, etc.

Based on these considerations, the scope and uncertainties of the safety cases presented in this report will be re-assessed, reflecting available site-specific information and considering how key uncertainties will be handled in case the site goes forward to PI. It can also be noted that, in the case of a coastal site, the seabed will be considered in the LS as a potential footprint for the repository.

(ii) Preliminary investigation stage

In the PI, a wider range of information will be obtained through field work. The geological information obtained will be integrated into a 4D SDM, which will be the basis of tailoring potential designs of HLW/TRU waste repositories and conducting associated safety assessments.

In creating the safety case at the PI stage, it is considered that the following would be specific examples of such studies:

- Construction of a more detailed repository scale SDM, based on geological environment information obtained from measured values, such as the three-dimensional distribution of potential host rock(s) and the mechanical and hydraulic characteristics of these and surrounding formations. It is accepted that both characterisation and development of the SDM might be more complicated if the geological setting of the sites differs greatly from those assessed in this report. Practicalities of the actual investigations will also differ, especially if potential host rocks are located under the seabed.
- It will be important to capture past, ongoing and future changes of the sites, such as sea-level change and uplift/erosion. Methods for 4D site descriptive modelling already tested will be applied and further developed. This would be especially important for a coastal location and it is essential that the required assessment tools and databases will be available for this assessment.
- Repository design(s) and layout(s), including installation location and depth, adapted to site conditions as captured in the SDM, would be developed for further assessment of safety before and after repository closure. In case siting environments strongly deviate from those studied in the current safety case, this might imply a need development of new repository concepts suitable for these sites.
- Confirmation of implementation practicality, based on engineering technology verification tests related to construction, operation, and closure of the designed repository.
- Measures to ensure safety of the repository before closure and to protect the surrounding environment will be further developed. There will also be special focus on the safety of construction and an integrated assessment of interactions between construction and operation will be needed.

- Application of RN migration model and parameters that more realistically reflect the characteristics of the designed repository, the host rock and groundwater chemistry. Also modelling of the biosphere that takes into account the surface environment and human lifestyle of the site.
- As identified in Section 7.3.2 a key objective would be a much more comprehensive safety assessment, determining the importance of remaining uncertainties, based on a more realistic abstraction of site and design information and using less conservative assumptions in the consequence analysis. Thereby, the safety assessment could provide key feedback on what may need to be explored during the DI stage.
- Based on the findings from a more comprehensive uncertainty assessment, the potential for optimisation of repository designs will be assessed.

When selecting a DI site, it may be necessary to compare repository designs for each of the PI sites. It is important that such designs consider site-specific environmental conditions and include optimisation based on design factors. Here the safety case can be useful to support comparisons, improving transparency in the choice of DI. The uncertainty analysis will be very important in this respect, as the effort required to reduce uncertainties may be very site specific. Limitations on direct accessibility to the suitable host formations could potentially be handled by locating the surface and underground facilities far apart, which then need to be connected by an underground access tunnel. This could, for example, be the case if the suitable host rock is located offshore. Different options have to be compared in terms of pros/cons in a structured manner. Furthermore, the situation may arise that there will be no single suitable formation at a potentially site suitable for both HLW and TRU, as well as the locations of surface and underground facilities

(iii) Detailed investigation stage

The key aim of the DI-stage is to develop an optimal site-specific repository design, proven to provide both operational and post-closure safety through a comprehensive safety case. Detailed planning of the DI stage would have to wait until the PI stage is underway, since the relative importance of different issues will strongly depend on the knowledge gained during the PI stage.

Following further surface-based investigations, the DI stage involves constructing a site-specific underground investigation facility (UIF), allowing both underground investigations and demonstration tests of the engineering technology [77]. An updated SDM and repository design / layout adapted to this model will be developed. Based on this, and other scientific knowledge obtained, the safety case will be refined. This will determine if the site conditions, technology and other information necessary for applying for a repository construction license are in place.

Since the DI stage could lead to a decision to start construction of a repository at the site, it is essential that the underground activities in the UIF are planned such that they would not cause unnecessary perturbations to the host formation that might impair its suitability. Tests and data from generic URLs should thus be utilised to the extent possible. Development of repository designs and installation techniques would not necessarily require access to the actual host formation and several research issues could, at least initially, be studied elsewhere.

7.4.2 Fundamental safety case improvements

In addition to tailoring the safety case to the siting process, there are other fundamental, site-independent improvements that are needed to keep a safety case fit for purpose over a period in the order of a century, as discussed further below.

(1) Continuous improvement of safety cases

NUMO will improve the assessment basis for safety cases by continuing to tackle the issues identified in the R&D plan, as described in Section 7.3.3 (1). Such improvements concern the scientific and technical knowledge base, modelling technology and approaches to verification and validation. These issues are common to all sites, with continuous improvement of the confidence of safety cases essential when assuring the general feasibility of safe geological disposal in Japan. This is important from the viewpoint of encouraging more communities to accept a LS, since safety is a critical issue for discussions to support gaining understanding and establishing credibility.

When a site is identified, NUMO will proceed with production of a site-specific safety case that reflects the characteristics of that location. For this also, the assessment basis needs to be continuously improved, with this safety case developed while site investigations ongoing. In this way, issues specific to site conditions will be clarified, with plans flexibly reviewed so that any R&D necessary can be carried out for these issues.

There are restrictions on the human resources and budgets available for producing safety cases and associated R&D. Thus a balance is needed between efforts on more generic issues and those focused on site-specific safety cases. As the site selection progresses, and narrows down to a few locations, efforts to improve the confidence of the site-specific safety cases will be the main priority. Nevertheless, even in this case, it is necessary to maintain the R&D framework to provide a wider perspective of key knowledge areas included within the assessment basis.

(2) Maintaining state-of-the-art technology and knowledge base

In addition to the considerations above, as part of general confidence building it is important to advance research and development according to R&D plan mentioned in Section 7.3.3. To promote this effectively, NUMO takes part in the Coordination Council on R&D of Geological Disposal and also conducts joint research with overseas organisations through participation in international joint projects (see Section 7.3.3 (2)). Thereby, NUMO will continue to maintain state-of-the-art knowledge related to safety cases and geo-environmental characterisation technology while conducting planned work during the LS, PI and DI stages. This will also include a accumulating explicit and tacit knowledge required to conduct demonstration tests as required at different stages of the siting programme.

The development of both the requirements and knowledge management systems described in Section 7.3.3 (4) can be expected to be an effective tool for efficiently and appropriately managing the different R&D issues that will need to addressed after sites are identified. Considering the long period during which the disposal programme will evolve, these management tools will also continue to be maintained at the state -of-the-art.

(3) Optimisation of repository design and implementation

As emphasised previously, safety is an absolute requirement, but the more holistic overviews provided by advanced safety cases may allow this to be assured while optimising other aspects of the overall repository implementation programme, such as social acceptance, cost, sustainability, environmental impact and spin-off benefits (e.g. utilisation of repository heat, spoil, etc.).

The design process described in Chapter 4 considers different design factors that need to be addressed in the project implementation, such as operational safety, post-closure safety, engineering feasibility, retrievability, environmental impact, and socio-economical aspects. These design factors lead to requirements on repository components and their specifications (materials, configurations, dimensions, etc.), and it needs to be ensured that all requirements are sufficiently met, with explicit considerations of any trade-offs that may be required. Therefore, development of a clear methodology for performing overall optimisation is an important issue to be addressed in the future (see Section 7.2.1 (2) (iv)). Here, the design factors and the requirements related to them are defined in association with the upper-level requirements systematically managed by the RMS described in Section 7.3.3 (4).

Starting from the generic safety case presented in this report, Figure 7.4-2 displays how site-specific safety cases lead to repository design optimised in light of design factors, assuring that it conforms to the site environmental and geological conditions that are gradually refined by the site survey, and thus leads to selection of a preferred site/concept for license application. Within this process, repository design considers requirements that go beyond purely technical issues, but the safety case can act as a basis for soliciting stakeholder input to relevant decision-making [78].

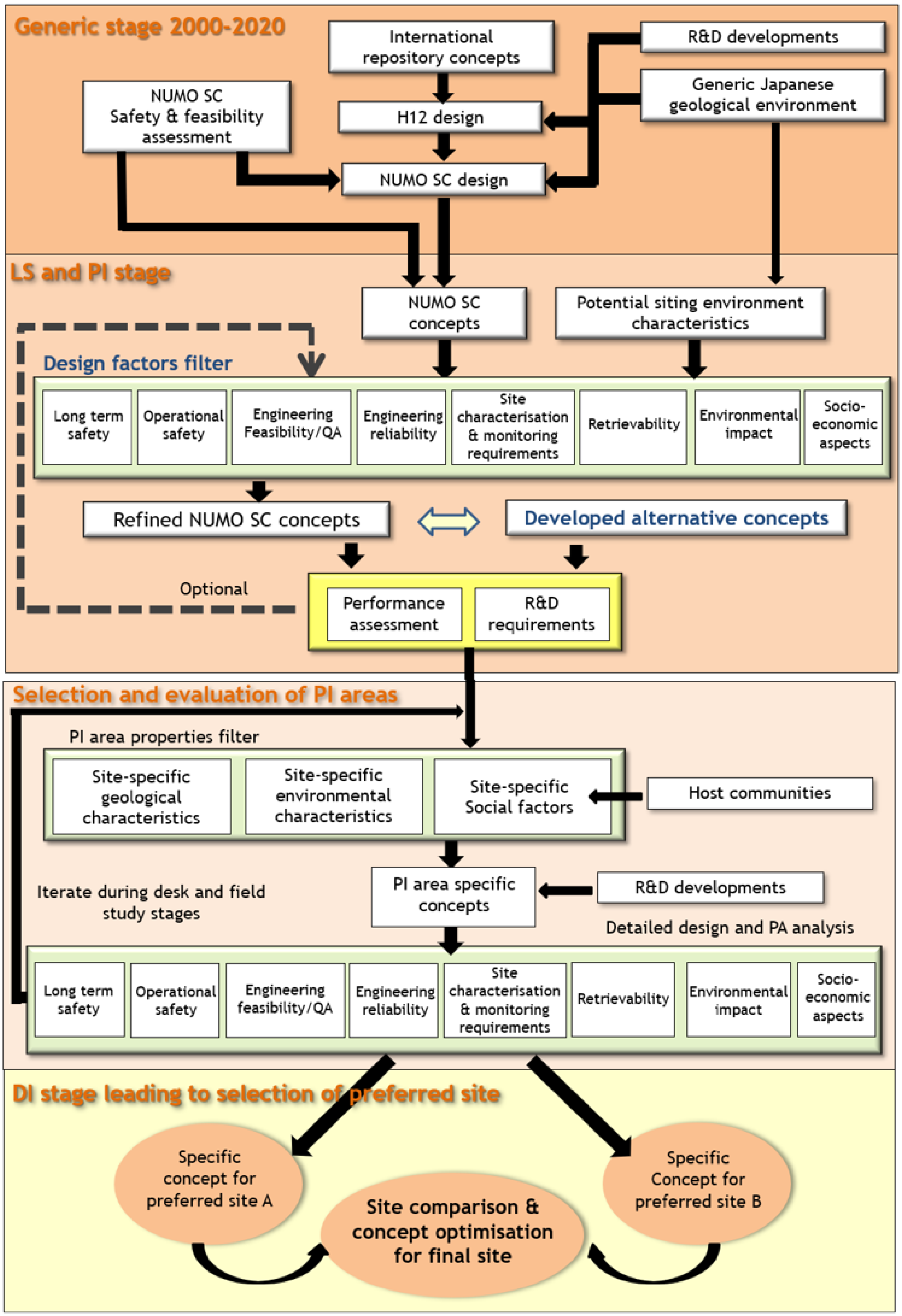


Figure 7.4-2 Repository design development on the basis of site-specific safety cases

7.5 Summary

This chapter demonstrates that NUMO has established methodology for selecting favourable geological environments and developing SDMs for representative host rocks, established an approach for designing a repository for such SDMs with the required safety features that is consistent with the current state-of-the-art, and established methodology, tools and data that form a sound basis for assessment of the safety of these disposal concepts in such geological environments. These have been integrated into the current safety case, which provides the knowledge base required in order to proceed with siting after the Literature Survey commences in volunteer communities. This chapter also functions as a standalone description of the Safety Case for readers who have not read the other chapters. Thus, some of the key findings in earlier chapters are summarised, but the chapter also adds additional elements needed for a safety case. The latter includes supporting arguments for post-closure safety in terms of complementary indicators, supporting arguments from natural analogues and comparison with other safety cases, as well as an identification of limitations and constraints on the current safety case.

In order to move further in developing safety cases to support the siting programme, further development is needed. For this reason, an outline of the strengths and limitations of the present safety case serves to identify and prioritise the technical R&D needed to build the knowledge base to support literature searches at volunteer sites, stepwise site investigations and design tailoring leading to site/design selection and, eventually, repository implementation. Additionally extensive development aims to support production of increasingly detailed site-specific safety cases, which involves both development of methodology to manage the production process (e.g. advanced requirements and knowledge management tools) and assuring availability of essential resources – in particular experienced staff. Finally, the wider role of the safety case in decision-making during stepwise siting is outlines, with special emphasis on establishing dialogue with non-technical stakeholders and bringing them into the decision-making process.

Supporting Reports (SRs)

SR 7-1 The concept of complementary performance indicators
SR 7-2 Evolution of radioactivity in components of the geological disposal system
SR 7-3 Evolution of radiotoxicity in components of the geological disposal system
SR 7-4 Alternative indicator of release: potential radiotoxicity in river water
SR 7-5 Natural analogues
SR 7-6 History of external review

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8 SUMMARY AND CONCLUSIONS

The aim of this report is to assess the basis for ensuring safe geological disposal of HLW and TRU waste for the geological environments found in Japan, from NUMO's perspective as a repository implementer. Based on the latest scientific knowledge and the results of technological development to date, this report presents a preliminary safety case for repository concepts tailored to representative geological environments. As such it will provide a basis for both initiation of site investigations, and, to guide further activities in research, development and design work. In accordance with the IAEA glossary [1] a safety case in this early stage of development should acknowledge the existence of any unresolved issues and should provide guidance for work to resolve these issues at future development stages.

In this report, the following elements are presented:

- The methodology for selecting appropriate Japanese geological environments to host a repository for disposal of HLW and TRU wastes is illustrated. This leads to capture of understanding in three representative site descriptive models (SDMs) to serve as the basis for the design and safety assessment of a repository. The process of SDM development also leads to identification of the approaches and technology required for future site-specific investigations.
- The methodology for repository design of to meet the requirements for safety and engineering feasibility is developed and examples of design specifications are given for each SDM. The development and demonstration of the individual technologies required to construct, operate and close a repository based on the design, is shown to be progressing steadily and priorities for future technological development are identified.
- A series of methods and analytical techniques have been developed to assess the safety of the repository, before and after closure, reflecting the characteristics of the SDMs and the repository designs tailored to them. These form the basis for safety assessments that illustrate how specified safety functions of the repository system can be evaluated and assessed against refined performance targets in terms of radiological impacts.
- In order to further improve the reliability of the techniques for investigation and evaluation of the geological environment, repository design and safety assessment, and to increase their applicability to expected volunteer sites, this report identifies issues that need to be addressed in the future. In this way, the direction of technological development for the implementation of this long-term project is indicated. In addition, NUMO is laying the groundwork for quality and knowledge management and human resource development to support the project.
- The safety case presented in this report will be updated and extended to build confidence in the safety and practicality of geological disposal projects in a stepwise manner as the investigations leading to site selection and eventual repository licensing proceed.

In accordance with the goals and boundary conditions set for this report in Chapter 2 it is demonstrated that NUMO has:

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