NUMO
原子力発電環境整備機構

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Development of Repository Concepts for Volunteer Siting Environments

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Nuclear Waste Management Organization of Japan (NUMO)

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Science and Technology Department
Nuclear Waste Management Organization of Japan
Mita NN Bldg. 1-23, Shiba 4-chome, Minato-ku, Tokyo
108-0014 Japan
Phone +81-3-4513-1114   Fax +81-3-4513-1599

Preface

The primary objective of government policy, and of NUMO in implementing this policy, is to ensure that a repository for Japan's high-level radioactive waste is designed and located so as to provide secure isolation of the waste and adequate safety for present and future generations. This requires that the site of a repository has to be chosen carefully and an associated repository concept is selected which is appropriate for its specific geological and environmental conditions.

At NUMO, we have chosen to implement a volunteering approach to siting. This is constrained by the use of "Siting Factors" which ensure that only locations which have sufficient geological stability are considered – an important factor in a country like Japan which lies in a tectonically active region. The potential diversity of volunteer sites puts particular constraints on the process of repository concept development – requiring that we maintain a range of possible options to ensure maximum flexibility to tailor this concept to the conditions found at a particular site.

Our term "Repository Concept" includes not only the design and layout of the disposal system but also the associated evaluation of operational and long-term safety and an assessment of socio-economic aspects. A particular challenge lies in the development of such concepts in an open and transparent manner which allows all key stakeholders to become actively involved, particularly the community hosting the facility and its neighbours. A logical structure allowing systematic development of repository concepts has been established, taking into account the close linkage between site information, repository design and safety assessment. We think it is very important to identify such a logical structure from the outset of the siting programme, which can be consistently applied to later site investigation stages.

This report outlines the background, principles and status of our repository concept development work and discusses how it might progress during our staged siting and implementation programme. A companion report (NUMO, 2004) discusses the development and application of the previously mentioned Siting Factors.

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1 INTRODUCTION

1.1 NUMO and its mission

NUMO – the Nuclear Waste Management Organization of Japan – was established in October 2000 on the basis of the Specified Radioactive Waste Final Disposal Act (the "Act") promulgated in June 2000. In this Act, we are given the clearly defined remit to develop a project for the safe disposal of vitrified high-level radioactive waste (HLW). As indicated in Figure 1-1, NUMO operates within a network of government and other relevant organisations which have complementary responsibilities for the technical, legal, regulatory and funding activities associated with HLW disposal in Japan.

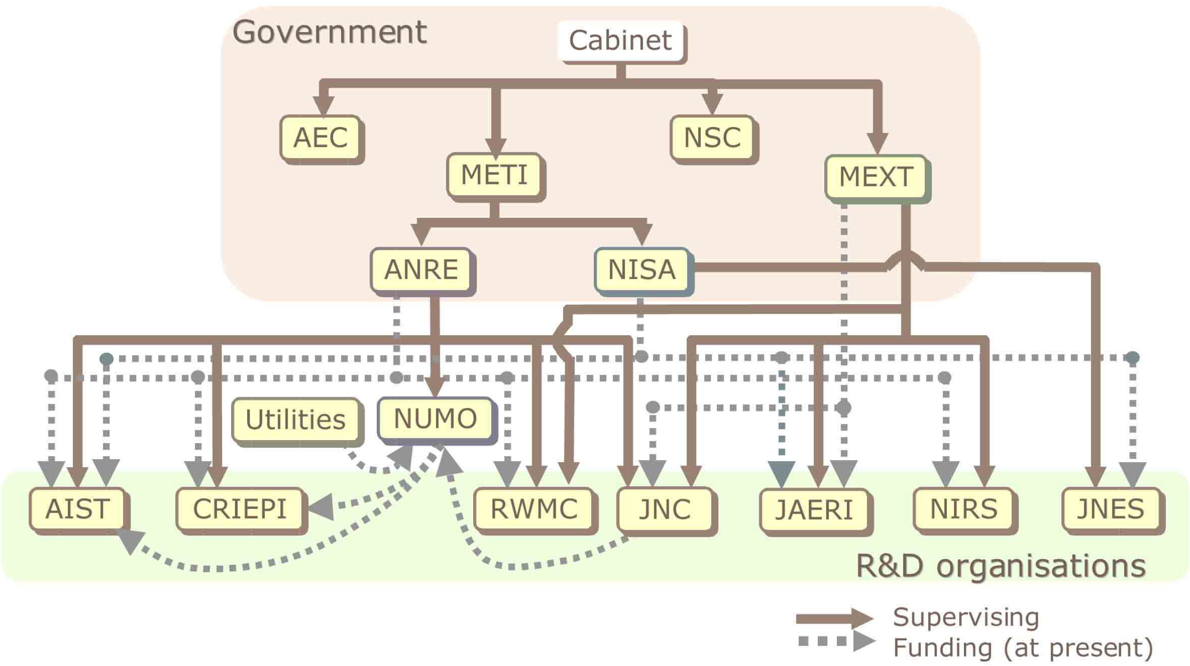

Figure 1-1: NUMO in the context of the Japanese HLW disposal programme.

Acronyms:

AEC: Atomic Energy Commission (http://aec.jst.go.jp/jicst/NC/eng/index.htm)

NSC: Nuclear Safety Commission (http://www.nsc.go.jp/english/english.htm)

METI: Ministry of Economy, Trade and Industry (http://www.meti.go.jp/english/index.html)

ANRE: Agency for Natural Resources and Energy (http://www.enecho.meti.go.jp/english/index.htm)

NISA: Nuclear and Industrial Safety Agency (http://www.nisa.meti.go.jp/english/index.htm)

MEXT: Ministry of Education, Culture, Sports, Science and Technology (http://www.mext.go.jp/english/index.htm)

NUMO: Nuclear Waste Management Organization of Japan (http://www.numo.or.jp/english/index.html)

JNC: Japan Nuclear Cycle Development Institute (http://www.jnc.go.jp/jncweb/02r-d/02index.html)

JAERI: Japan Atomic Energy Research Institute (http://www.jaeri.go.jp/english/index.cgi)

NIRS: National Institute of Radiological Sciences (http://www.nirs.go.jp/ENG/nirs.htm)

RWMC: Radioactive Waste Management Funding and Research Center (http://www.rwmc.or.jp/)

AIST: National Institute of Advanced Industrial Science and Technology (http://www.aist.go.jp/index_en.html)

CRIEPI: Central Research Institute of Electric Power Industry (http://criepi.denken.or.jp)

JNES: Japan Nuclear Energy Safety Organization (http://www.jnes.go.jp/english/index.html)

The Act restricts NUMO's responsibility to the consideration of "specified" radioactive waste – which is defined to be HLW resulting from the reprocessing of spent fuel from commercial power reactors.

The Act is also prescriptive in terms of the management option to be followed. It specifies deep geological disposal in Japan at depths greater than 300 m below surface. Also specified are requirements for geological stability and avoiding conflict with natural resources. The phased process of developing a siting project, involving more detailed characterisation as options are narrowed down, is also outlined in the legislation.

Following extensive discussions with many stakeholders, NUMO decided to take a rather innovative approach to the siting process. Based on consideration of international experience in repository siting, we recognised local acceptance as a critical issue which is essential to the success of such projects. We thus decided on a policy of calling for volunteer communities that would be willing to consider hosting this facility.

We sent a call for volunteers to all 3,239 municipalities in Japan in December 2002. Of course, potential host sites must also satisfy important geological and technical requirements. Accordingly, the documentation accompanying the call included an explicit specification of exclusion criteria which would be used to filter out clearly unsuitable sites[1]. These criteria were based on the geological stability requirements noted in legislation and the associated documentation included maps showing areas that would be clearly ruled out – e.g. due to risk of volcanic activity or the presence of major active faults. Even if a site is not excluded by such criteria, implementing a repository may be impractical or other volunteers may be more suitable. A range of other selection factors ("Favourable Factors") have thus been defined which will allow the staged siting process to proceed in a transparent manner (described in detail in NUMO, 2004).

We have been accumulating an inventory of relevant resources of information and experience available in Japan and via our international partners. This forms the starting point for identifying and prioritising further Research and Development (R&D) which we will need to initiate in order to establish a Japanese repository project. The present report comprises a review of the status in one particular area – the development of "Repository Concepts" (see the box in Section 1.3) appropriate to the siting environments defined during the volunteering process. This term "Siting Environment" includes not only the geological setting but also all other site features which influence repository implementation – such as geography, topography, socio-economic constraints and transportation infrastructure.

A companion report (NUMO, 2004) describes the Siting Factors for the staged site characterisation and evaluation process and places them in the context of the geological setting of Japan. In practice, the repository design and site characterisation processes are strongly coupled and develop in an iterative manner, with safety assessment during the various stages leading up to repository implementation.

These reports reflect NUMO's commitment to a policy of openness in its dealings with all interested parties. More extensive Japanese language reports covering the same topics are

[1] English translations of the documents supporting the call for volunteers, "Information Package" can be ordered via the NUMO website (www.numo.or.jp/english/what/index.html).

aimed at the potential volunteer communities and relevant organisations in Japan. There is thus a particular focus on the technical detail to support the call for volunteers. It should be emphasised that the English language documentation is not a translation, but is completely reworked to provide the background needed to enable a productive exchange of views with an international technical audience.

The Japanese report on repository concepts provides an overview of the status of international thinking on the fundamental concepts supporting development of a geological repository programme, covering for example:

- Stepwise implementation;
- Components of a safety case;
- Reversibility and retrievability;
- Ethical concerns.

Such a review is not included in this document, but all such issues have been taken into account in the development of our programme, as described in the following sections.

1.2 The repository development programme and milestones

Japan has an active nuclear power programme which includes an installed capacity of about 46 GW(e). Plans exist to expand nuclear power generation further and to extend the life of nuclear power plants based on careful safety review and maintenance (AEC, 2000). This strategy is designed to maintain the stable power production required by an industrial nation, while complying with requirements to reduce emissions of greenhouse gases from the combustion of fossil fuels. The decision to reprocess spent fuel reflects this long-term vision of nuclear power generation, which results from Japan's lack of significant resources of uranium and its commitment to sustainable development, which encourages all such recycling activities.

Presently, spent fuel from Japanese reactors is reprocessed in the UK or France and vitrified HLW returned to Japan for interim storage in a special facility at the Rokkasho site of Japan Nuclear Fuel Ltd. (JNFL) as shown in Figure 1-2(a). On a pilot scale, fuel has also been reprocessed and HLW produced by JNC at Tokai (Figure 1-2(b)). In the near future, a full-scale reprocessing plant will become operational in Japan – also run by JNFL at Rokkasho.

For a continually developing programme, establishing a time plan for implementation requires a balance to be struck between various technical and socio-economic considerations. For example, the technical advantages of storing reprocessed waste prior to disposal for as long as possible, in order to reduce radiogenic heat output, needs to be balanced against the ethical goal that the generation benefiting from nuclear power should also implement, or at least initiate, projects to ensure safe management of resulting wastes. Recently, another argument for accelerated implementation of deep geological disposal projects has focused on national security, due to the reduced vulnerability of underground facilities to possible terrorist threats.

Figure 1-2(a): JNFL Vitrified Waste Storage Center (left) and HLW storage pits (right) (photos: courtesy of JNFL).

Figure 1-2(b): JNC Tokai Reprocessing Plant (left) and HLW storage pits (right) (photos: courtesy of JNC).

In Japan, the planned development programme for a first HLW repository is outlined in Figure 1-3. This is based on an assumed capacity of 40,000 waste packages each containing 150 litres of vitrified waste, corresponding to reprocessing of all spent fuel expected to be produced up to 2020. The vitrified HLW will be stored for 30-50 years before disposal (MITI[2], 2000a). According to the Final Disposal Plan (MITI, 2000b), repository operation would start in the late 2030s, with an annual emplacement of 1,000 canisters of vitrified HLW.

Following our call for volunteers, the siting process is planned to proceed in a staged fashion. The first stage involves use of literature information to determine the basic suitability of each volunteered site in the light of established exclusion criteria, and to rank sites, in the event that there are more volunteers than can go through to the second stage of field characterisation. Such ranking may also be useful to set priorities and help plan the strategy for subsequent site characterisation, repository design selection and associated performance assessment.

The initial field characterisation of "Preliminary Investigation Areas" (PIAs) is restricted to work carried out from the surface. Following this stage, sites are again compared and a reduced

[2] Ministry of International Trade and Industry (now METI).

number carried on as "Detailed Investigation Areas" (DIAs), in which an underground characterisation facility is constructed to allow the deep geological environment to be examined in more detail. According to this plan, a site would be selected, the associated repository concept specified and the licensing process initiated in the late 2020s, allowing construction to commence around 2030 with first waste emplacement in the late 2030s. The time plan shown in Figure 1-3 assumes that, to some extent, construction, waste emplacement and sealing of emplacement tunnels proceed in parallel and emplacement operations are completed by the mid- to late 2070s. As discussed later in this report, there are a range of other possible options. We also leave open a possible period of monitoring and institutional control, with final closure thus being sometime after 2080.

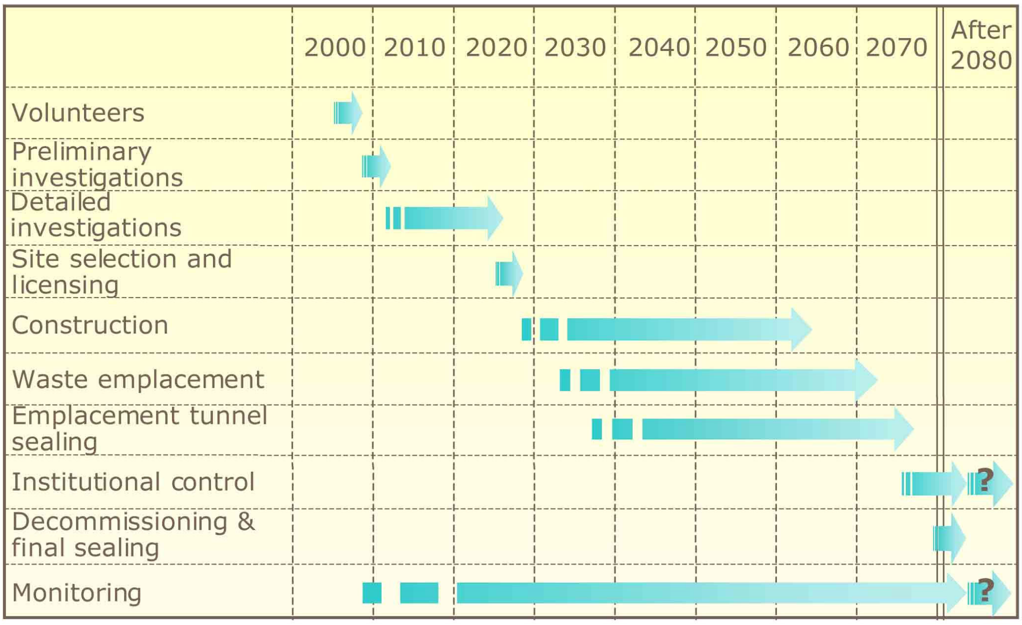

Figure 1-3: The staged repository development programme and possible milestones. The time plan after site selection has a model nature as it will depend, to some extent, on the repository concept selected.

1.3 Requirements for repository concept development

Box 1
Definition of a Repository Concept

We define a "Repository Concept" as a conceptual design of all surface and underground repository structures tailored to a given siting environment, along with a description of how the repository can be constructed, operated and sealed. This also includes an evaluation of operational and long-term safety and an assessment of socio-economic impacts. The concept is dynamic, evolving with our programme as it moves from early generic studies through to siting and, eventually, licensing for construction and operation. Indeed, continual evolution during the operational period is also possible, as experience is gained and technology develops.

The key components of the Japanese HLW disposal concept are based on work carried out over two decades by a range of R&D organisations, led by JNC, before NUMO was established.

This work, most recently summarised in the H12 reports (JNC, 2000), involved a generic evaluation of the requirements for a safe repository in the types of rocks and geological environments expected to be found in Japan. The basic repository design developed by JNC involved sealing vitrified waste in a thick steel container (the "overpack"), which is surrounded by a highly compacted bentonite layer (the "buffer"). A number of variants of the emplacement layout and the materials involved were examined in the H12 study, but there was no attempt at optimisation to improve operational practicality or to match the exact conditions to be expected in site-specific host rock environments.

Since NUMO was established, we have attempted to build on these foundations in order to develop designs appropriate to the diversity of particular sites which may result from the volunteering process. To do this, we have had to review the earlier designs carefully, particularly with regard to practicality of implementation under the conditions of a working repository and the strict operational safety and quality assurance requirements involved in any nuclear facility. This review has been extended to cover repository concepts which have been considered in other national programmes, as discussed in Section 2.3. Our decision to adopt a volunteering approach to siting results in further boundary conditions being necessarily left open – in both technical (e.g. area and volume of suitable rock) and socio-economic areas (e.g. extent of monitoring for confidence-building, institutional control, ease of retrieval).

The repository concept will develop in a staged manner – taking a range of repository design options (RDOs) into account and becoming more detailed as siting environments become better defined during the volunteer siting process. As the repository concept both requires input from, and provides guidance for, the site characterisation work, these efforts will be closely co-ordinated. This approach is presented in Figures 1-5 and 1-6 in Section 1.5.

1.4 Timescales and long-term safety

Japanese regulations specifying the long-term safety requirements for a HLW repository and defining how compliance with these requirements will be assessed are only now in the process of being drafted. Presently, we assume that regulatory guidelines in terms of dose and risk criteria and assessment timescales will be similar to those already established in a number of other countries. In all cases, the regulations and the corresponding safety concepts need to take into account the properties of the waste under consideration.

Figure 1-4(a) indicates that the period during which HLW can be considered to present a special hazard (in terms of its total radioactivity) compared to the original ore is in the order of tens of thousands of years. The radioactivity – and also the toxicity and heat output – of vitrified reprocessing waste is initially dominated by relatively short-lived radionuclides and decreases rapidly with time. After surface storage for 30 – 50 years, the most active nuclides remaining in the waste have half-lives in the order of decades and the radioactivity of emplaced waste drops by about 3 orders of magnitude over the first thousand years (see also Section 2.2). During this time, it is intended to completely isolate the waste and this led to the specification of a 1,000 year minimum overpack lifetime in H12 (JNC, 2000).

After a thousand years, the rate of decrease of radioactivity and radiotoxicity is less rapid. Nevertheless, after a few thousand years, the toxicity of the vitrified waste, based on the concentration limits which are specified in the current regulation for existing nuclear facilities

(STA[3], 1998; amended in 2000), has decayed to about the level of the uranium ore used to produce the initial reactor fuel (Figure 1-4(b)). This is compatible with the periods in the order of several tens of thousands of years considered as a minimum requirement for our assessment of site stability. Such a period can also be considered as the main focus for the demonstration of robust performance of the natural and engineered barriers.

Inevitably, assessments of performance become more uncertain with increasing time of extrapolation. Our quantitative analyses will, nevertheless, be extended into the distant future and attempt to, at least, bound the maximum consequences. Because the toxicity of the waste at such times has decayed to a level similar to natural geochemical anomalies, such formal analyses can be supported by more qualitative analogue arguments.

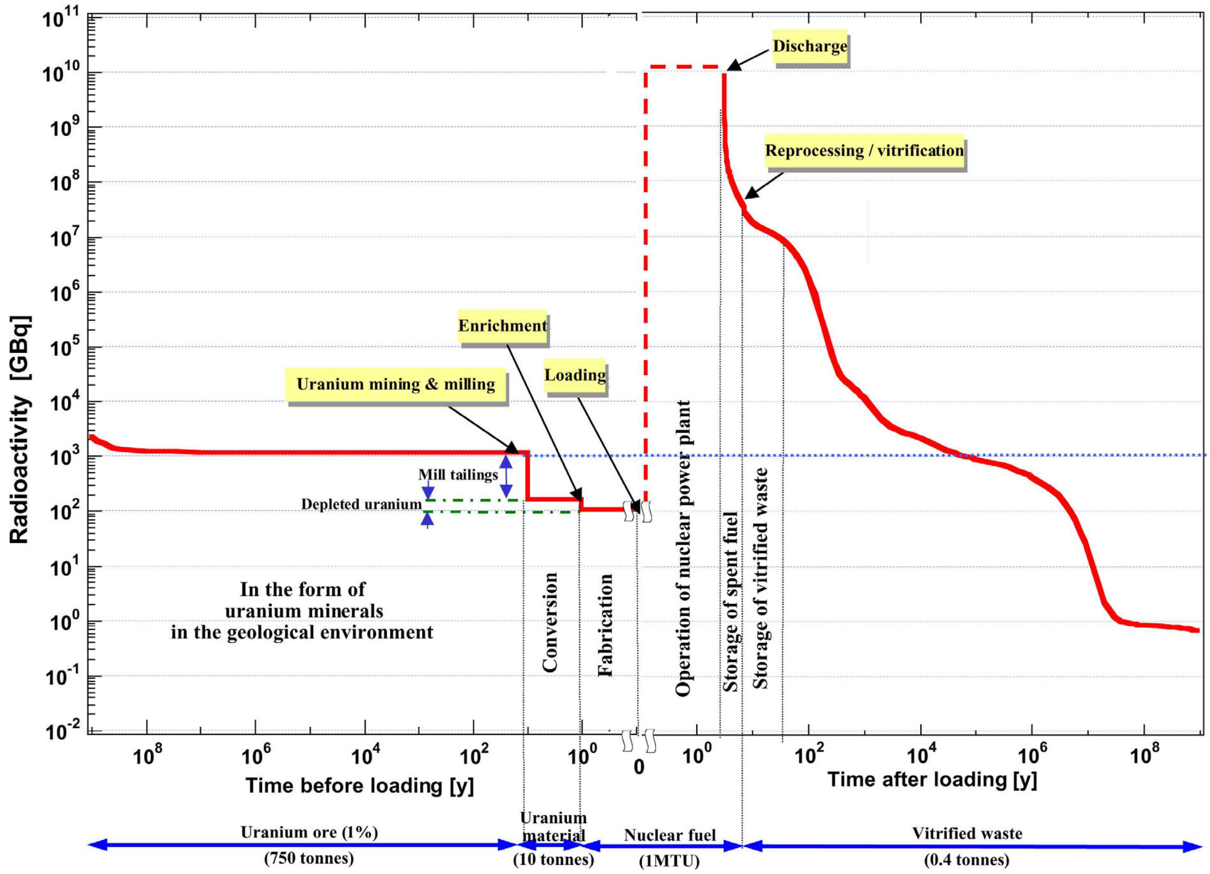

Figure 1-4(a): Characteristics of high-level waste from the viewpoint of evolution of radioactivity (corresponding to 1 MTU of 4.5% enriched fuel) (N.B.: L/ILW arisings from reprocessing are not considered.) (JNC, 2000).

[3] Science and Technology Agency (now MEXT).

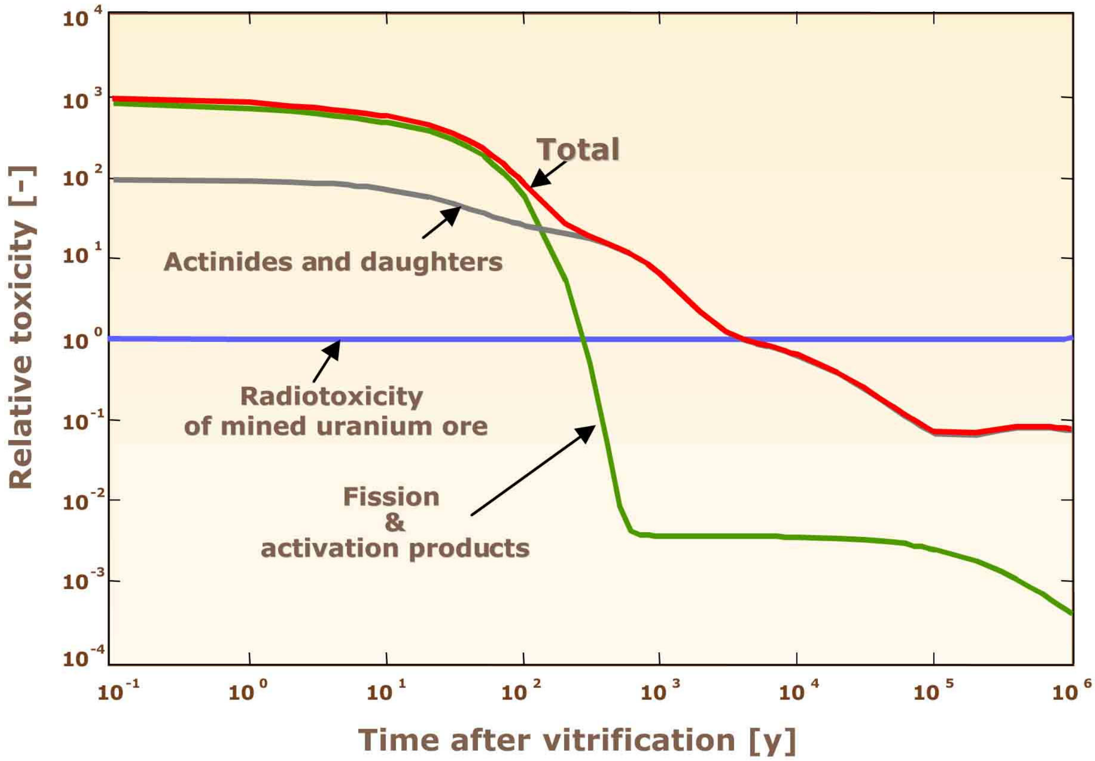

Figure 1-4(b): **The decay in radiotoxicity of vitrified high-level waste with time after manufacture. It can be seen that, while fission product radionuclides dominate radiotoxicity over approximately the first 100 years, actinide radionuclides and their daughters predominate thereafter. After about 3,000 years, the total radiotoxicity declines to the same level as that of the natural uranium ore used to manufacture the equivalent amount of fresh fuel from which the HLW was produced. The data are for one container of JNFL vitrified waste (with 4 years spent fuel cooling before reprocessing and immediate HLW vitrification) and the uranium ore required to produce 0.8 MTU of 4.5% enriched UO_2 fuel.**

1.5 Overview of boundary conditions and structure of this report

The constraints on, and input to, the NUMO programme as presented above are summarised in Figure 1-5. Thus, the focus on geological disposal defined in the Act means that NUMO does not investigate any alternative management options (such as indefinite storage or partitioning and transmutation). The Act also defines “specified waste” as HLW from reprocessing and this is where all NUMO’s efforts are concentrated. The specification of an inventory of at least 40,000 waste packages is seen as a sensible goal (covering a major part of the wastes produced by the current generation of nuclear power plants). A 40,000 package inventory is thus used as a planning basis, but flexibility for optimised utilisation of a suitable site is explicitly considered.

The specification by the Act of staged implementation is reflected in our process of initially selecting several PIAs which are then reduced to a few DIAs before a final repository site is selected. NUMO’s decision to proceed with a volunteering approach was driven by our recognition of the great importance of public acceptance. Taken together, these constraints explain why we have adopted an approach that aims to maximise the flexibility to tailor repository concepts to the diversity of suitable siting environments which may be found and to encourage involvement of local communities in decision-making.

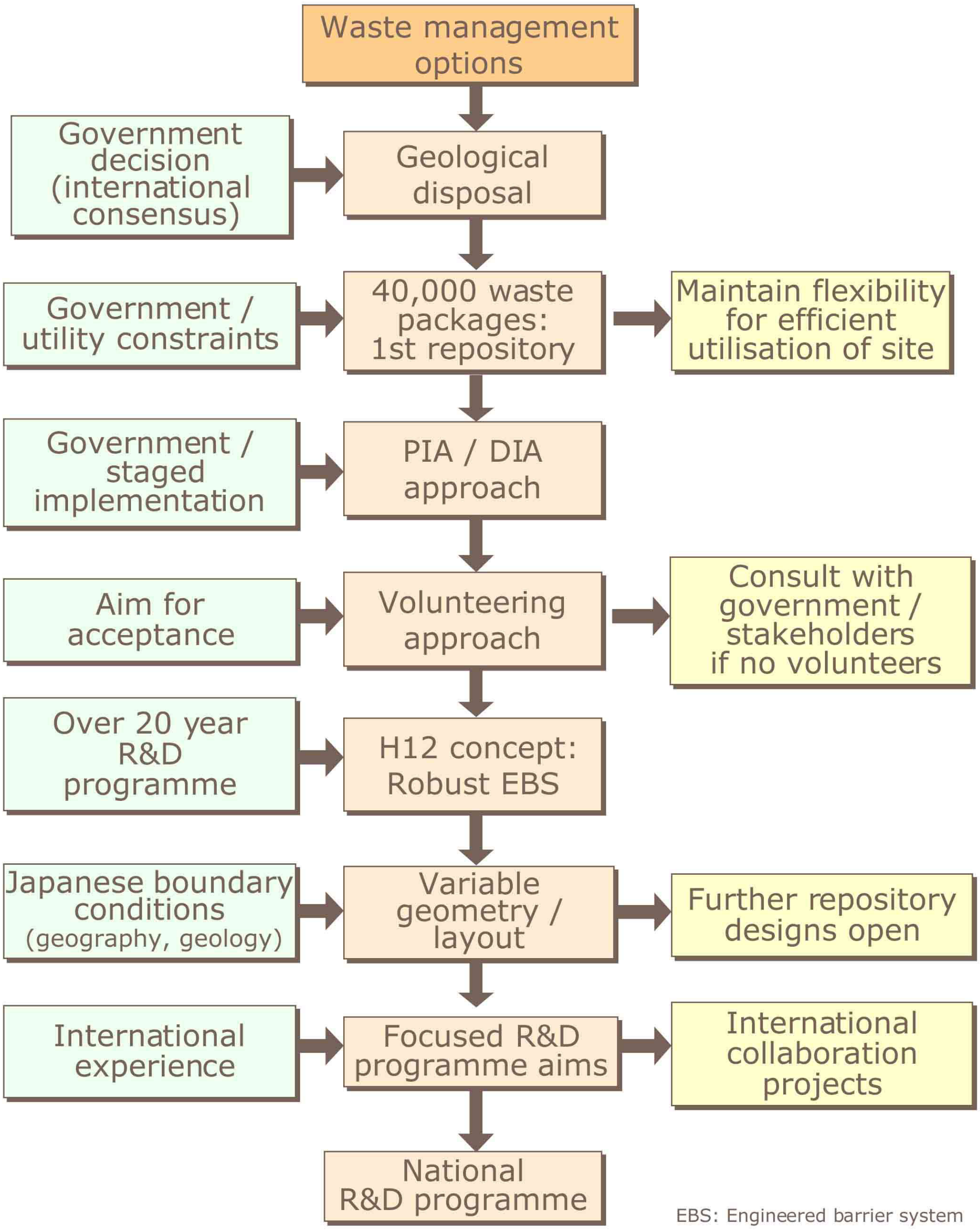

Figure 1-5: Constraints on the NUMO repository concept development programme.

The rest of this report is concerned with the more technical aspects of our preliminary investigations to develop appropriate repository concepts, to tailor these to specific volunteer site conditions, to assess their safety and to define the required supporting R&D programme.

The key features involved are illustrated in Figure 1-6. The starting point is set by over two decades of R&D experience, which was summarised in the H12 project (JNC, 2000). The geology of Japan places special constraints on site selection and an explanation of how these affect NUMO's approach is the focus of the companion "Siting Factors" report (NUMO, 2004).

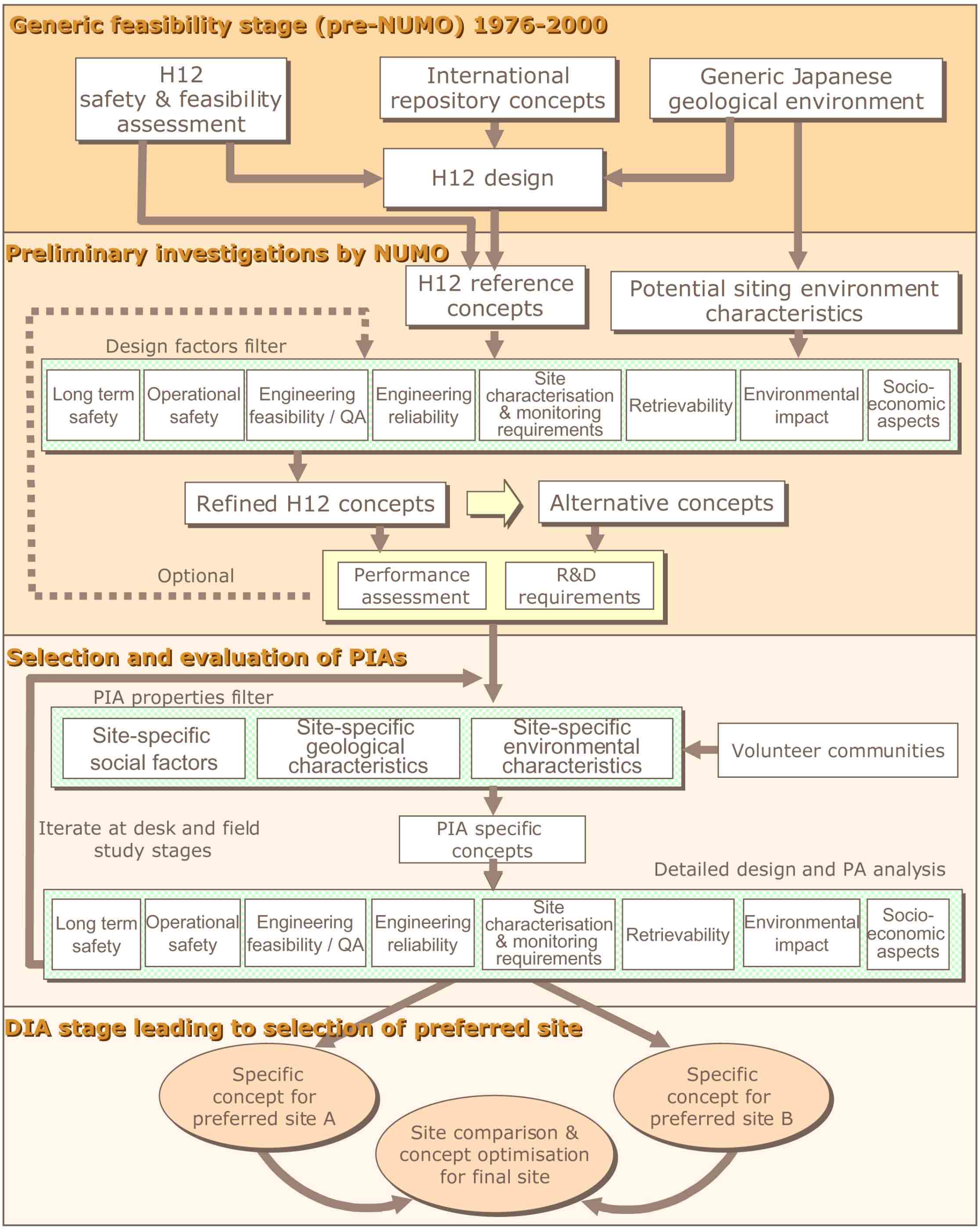

Figure 1-6: Repository concept development during the staged site characterisation process.

Chapter 2 expands on the basic principles involved in developing appropriate repository concepts for any suitable volunteers that come forward and introduces the concept of the design factors filter. It also provides a very general overview of the characteristics of the waste to be disposed of and the main features of the H12 concepts.

Chapter 3 focuses on the process of tailoring repository concepts to the environments found at a particular volunteer site and, in particular, on how to involve all relevant stakeholders in this process. Chapter 4 considers the critical aspect of safety - with special concentration on the timescales of most concern to the volunteer community. From the basis thus provided, Chapter 5 outlines the planned supporting programme of R&D.

Finally, Chapter 6 outlines how we expect the programme to develop as volunteers are characterised in increasing detail by desk and field studies and the site-specific repository concepts are iteratively optimised for the particular environments involved.

To improve the flow of text, the various repository components which are combined in order to produce RDOs are illustrated in Appendix 1. In contrast to repository design studies in other national programmes, this report places particular focus on operational phase safety. Post-closure safety is, nevertheless, a key consideration which cannot be compromised and is a special focus for Appendix 2.

2 BASIC PRINCIPLES

2.1 Design philosophy

At NUMO, we recognise the importance of establishing and maintaining a safety culture (see also Chapter 4). The focus on safety – and associated quality – should permeate NUMO and all associated partner organisations and contractors. As an implementing organisation charged with developing an economically feasible project, we also have to carefully consider practicality and costs (which are, ultimately, borne by the Japanese public as electricity consumers). It should be emphasised, however, that we do not see a conflict between ensuring safety and optimising costs.

Our design philosophy is reflected in a set of general principles and objectives for the repository design process, which could be regarded as embodying engineering "good practice". In our particular case, these are worth explicitly formulating because of our particular boundary conditions, which include:

- Lack of precedent for such a project;
- Very long planning and implementation timescales;
- Very long times over which passive safety must be demonstrated;
- As yet undefined, in principle stepwise, licensing procedure;
- Requirement for continuous public acceptance.

The foundations of this philosophy are:

1) Advance planning: Pre-emptive planning is essential; safety-relevant issues are identified as early as possible and steps taken to avoid the risk, or mitigate the consequences, of even improbable events. Given the timescales of decades involved in this planning, a rigorous system for requirements management (NEA, 2004) will be implemented to provide a trace of all key planning decisions.
2) Keep it simple: We aim for simplicity, with minimisation of the number of individual processes and components, bearing in mind that the emplacement procedure has to cope with 1,000 waste packages per year for 40 years (MITI, 2000b).
3) Robust design: Complementing the aim for simplicity, we aim for robustness by focusing on well tried and tested materials, processes and technology, including large safety margins and ensuring that equipment and procedures "fail safe" under all expected perturbation scenarios.
4) Integrated Safety & Quality Management: Designs of equipment and procedures include controls and checks to ensure that specified guidelines are adhered to at all times.
5) Operational zoning: As construction activities may run in parallel to handling of highly radioactive materials, establishment of clear zoning will act to constrain activities in particular areas and prevent any detrimental interactions between them.
6) Minimise degradation: As the geological barrier plays a key role in the safety case (see Chapter 4), we will develop procedures to avoid (or minimise) risk of degradation of sensitive areas (including the emplaced engineered barrier system (EBS)) during or after construction and operation of the repository.

7) Human factors: The repository development and operation timescale is such that several generations of staff will be involved, requiring special consideration of human interfaces in safety-critical operations.

8) Stakeholder involvement: Acceptance is essential to such a project and hence we envisage an active process, involving both openness and transparency in all our work and also working together with all stakeholders, including local communities, to develop consensus on key issues.

9) Economic constraints: It is fundamental to the principle of sustainability that invested effort (cost) should be appropriate to the problem and resources should not be squandered. Thus, cost / benefit analyses are carried out throughout the planning process.

Such principles are not absolute, but form a useful checklist to ensure that all critical factors are being considered during the development and documentation of repository concepts for specific siting environments.

In addition to setting out these practical principles, appropriate organisational structures will be established within NUMO to ensure that these principles are implemented. Such management structures include clear allocation of responsibilities and short chains of command.

2.2 Waste inventory

The wastes considered for disposal are vitrified high-level radioactive residues from reprocessing of spent fuel from commercial power reactors. They include wastes returned from reprocessing overseas, by BNFL in the UK and COGEMA in France. In addition, wastes will result from the JNFL reprocessing plant which is planned to begin operations soon at Rokkasho. A summary of the wastes which are expected to arise from reactor operations up to about 2020 is given in Table 2-1 and an indication of the typical waste properties in Figure 2-1. It is clear that the inventory has a model nature and that the characteristics of waste produced over the next couple of decades will reflect variations in reactor operations (e.g. fuel burn-up) and reprocessing / vitrification technology.

Table 2-1: Waste arisings (BNFL, COGEMA, JNFL & JNC reprocessing plants).

	BNFL	COGEMA	JNC	JNFL
Number of HLW canisters already produced and placed in storage (as of Jan. 2003)	616 (at JNFL)		130 (at JNC Tokai)	-
Number of HLW canisters equivalent to the spent fuel presently waiting to be reprocessed	~1,600		~970	~13,300
Additional planned arisings	-		-	~23,400
Totals	~2,200		~1,100	~36,700

N.B.: Based on the current programme, the total amount of vitrified waste is expected to reach ~30,000 canisters around 2013 and ~40,000 canisters around 2020 (MITI, 2000b).

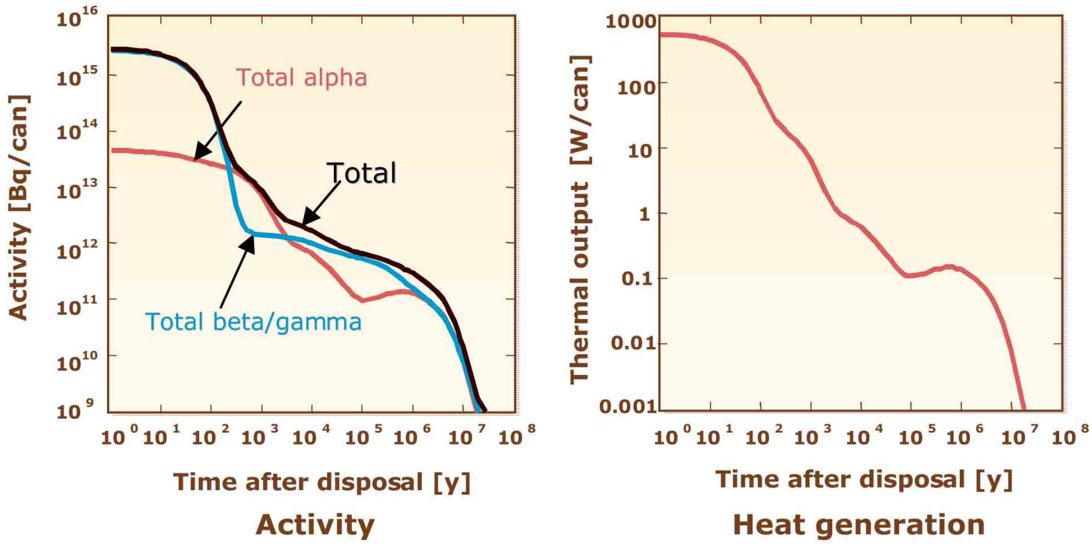

Figure 2-1: HLW properties (type: JNFL; cooling time before disposal: 50 years): Radioactivity and heat generation per canister of waste as a function of time after disposal.

2.3 Repository infrastructure

A repository basically consists of facilities for:

- Construction and maintenance of underground emplacement tunnels and / or boreholes, including power, drainage, ventilation, etc.;
- Reception, handling, temporary storage and packaging of vitrified waste containers;
- Transportation and emplacement of waste underground;
- Construction of other required engineered barriers;
- Monitoring and assuring security of operations.

As a medium-sized industrial facility, the repository requires a significant amount of additional infrastructure for the administration and support of the workforce involved.

In principle, there are two distinct sets of operations – those associated with construction (and closure) which do not involve any interaction with waste and those which involve the strict protection measures associated with the handling of radioactive material. It is generally expected that construction, waste emplacement and sealing of disposal tunnels will run – to at least some extent – in parallel.

Operationally, waste emplacement would involve remote handling activities in restricted-access zones. The extent to which all subsequent backfilling / sealing can be (or needs to be) done remotely may depend on the details of the design.

The long-term safety of a repository is assured by a combination of engineered and natural, geological barriers. Studies carried out over the last couple of decades have shown that, under the boundary conditions set by various national programmes, many different combinations of waste type / engineered structures and geological settings can provide high levels of safety (Figure 2-2).

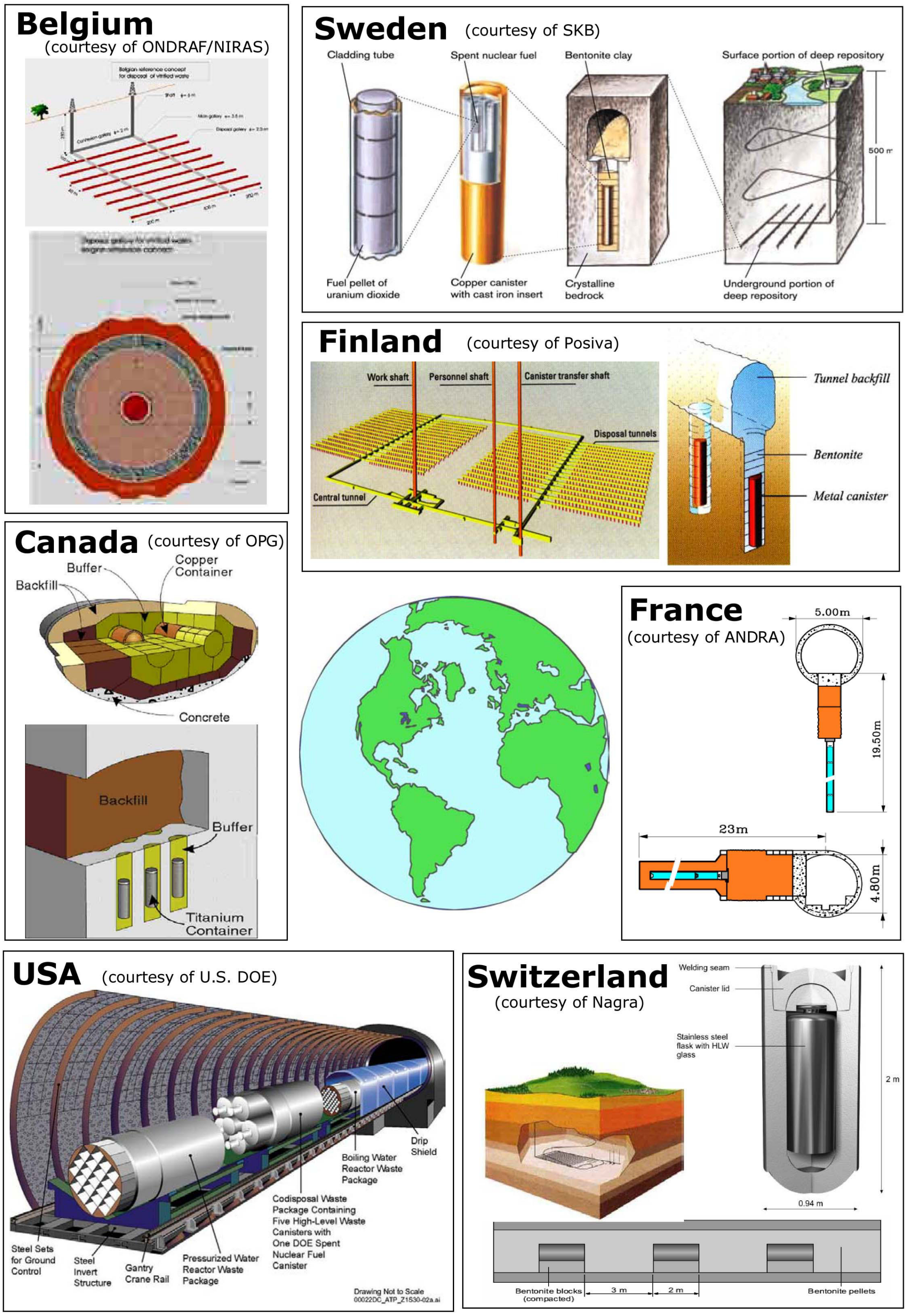

Figure 2-2: **Repository design variants considered in feasibility studies by different national programmes (ANDRA, 2001; Gierszewski et al., 2001; Nagra, 2002; ONDRAF/NIRAS, 2001; Posiva, 1999; SKB, 2001; U.S. DOE, 2002): These options are not yet finalised and may be modified significantly before the repositories are implemented.**

The key components of the H12 EBS developed by JNC are a massive steel overpack and a thick buffer of compacted bentonite / sand (JNC, 2000). These barriers were chosen to provide high performance, with a highly conservative design using well-known materials. Figure 2-3 illustrates the main features of this EBS and indicates the multiple processes which work together to provide a robust isolation system.

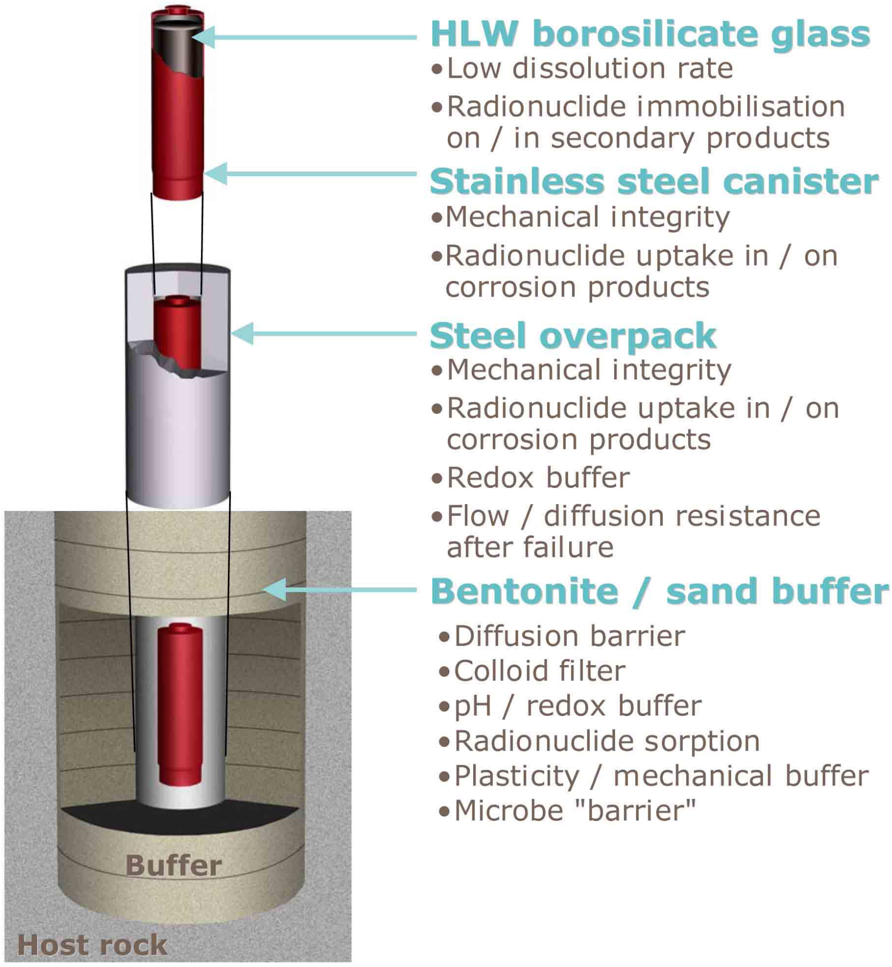

Figure 2-3: H12 engineered barrier system: components and potential roles (N.B.: not all these barrier roles were analysed in the H12 study).

In a stable geological environment, such barriers can ensure that radionuclides are completely contained for the period until the radiogenic heat has dropped to negligible levels and total radioactivity has decayed to a small fraction of its original level. Although the other engineered and natural barriers could efficiently retain the short-lived radionuclides decaying over this period, complete containment within the overpack over the period when there are thermal, hydrological and mechanical transients (which are coupled in the near field) greatly simplifies the resultant safety case – i.e. contributes to robustness.

Thereafter, following failure of the overpack, extremely slow dissolution of the waste will lead to eventual releases of long-lived radionuclides from the EBS, but the concentrations will be so low that there is no significant radiological hazard. A large proportion of the activity will decay completely within the EBS (and most of the rest within the geological barrier - see Figure 2-4).

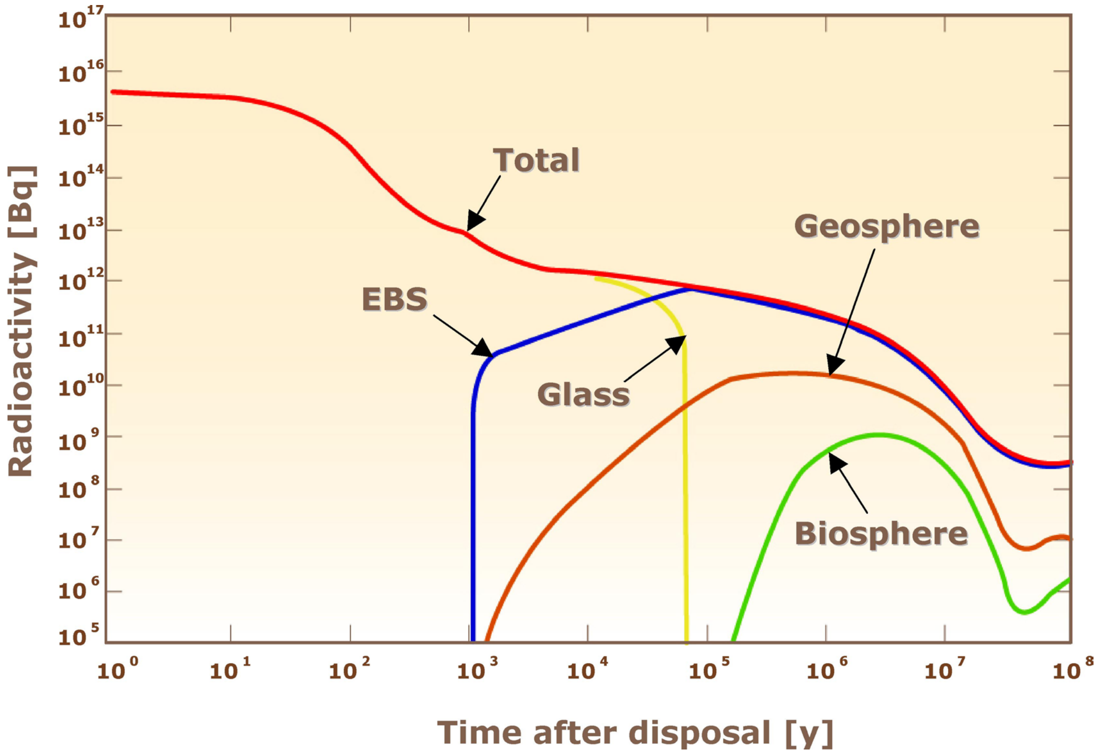

Figure 2-4: **Evolution of the distribution of all radionuclides in different system components as a function of time for the H12 Reference Case (after Makino et al., 2002). The curve labelled EBS represents all EBS components (Figure 2-3) excluding the glass matrix, which is shown separately.**

The characteristics of EBS materials and alternatives (e.g. Cu-Fe or Ti-Fe composite overpacks, various bentonite / sand buffer compositions) were extensively reported in the H12 project. Their behaviour and evolution with time is well supported by extensive laboratory studies, mechanistic modelling and natural analogues. An area which is less well defined, however, is the practicality of construction of such an EBS under strict quality assurance controls in an operational repository environment (considering underground conditions of restricted space, humidity, emplacement rate, remote handling, operational safety, robustness to perturbations, etc.).

In addition to these primary engineered barriers, a number of other repository structures may have barrier roles – e.g. tunnel liners, borehole caps, backfilling, plugs and seals for tunnels, ramps and shafts. As yet, the performance of such structures and their possible interactions with each other (and the primary EBS) have not been examined at a detailed level.

At NUMO, we have taken the decision to focus our efforts at present on the basic EBS components illustrated in Figure 2-3, with emphasis on improving our understanding of the areas of uncertainty noted above, rather than looking at a wider range of variants. This concentration of resources is justified by the extensive national and international experience with these particular EBS components in the planning of vitrified HLW disposal concepts in different host rocks. In terms of exact design, layout and operational procedures, this basic system also allows a wide range of implementation options, which can be tailored to specific geological boundary conditions or socio-economic requirements.

Even with this purposely narrowed range of EBS components, there are many different ways in which H12 and international experience can be combined to develop repository concepts. As an aid to developing designs, we have catalogued the various components of the repository (Appendix 1). This catalogue illustrates how, starting from the fixed point of the waste to be disposed of, a basic design for the repository system can be assembled by choosing between various options. Although, individually, there are no components included which are completely novel, specific combinations might be derived which have not been explicitly studied before.

As previously mentioned (see Figure 1-6), we have developed a strategy for iterative development of this basic repository concept as the process of site selection and characterisation progresses. Note that, although long-term safety is an essential requirement of all designs, we also take explicit account of the principles previously discussed. In order to assemble an RDO from the various components, we examine a set of “design factors”, each of which addresses an issue bearing directly on the chosen design:

- Long-term safety: robustness of the post-closure safety case;
- Operational safety: conventional and radiological safety of construction, operation, closure and decommissioning;
- Engineering feasibility / quality assurance: fundamental feasibility of construction and operation to defined quality levels;
- Engineering reliability: practicality of implementation in view of boundary conditions (e.g. emplacement rate) and robustness with regard to operational perturbations;
- Site characterisation / monitoring: effort required to satisfy technical requirements for site characterisation and monitoring data;
- Retrievability: ease of waste package retrieval after emplacement;
- Environmental impact: extent of all environmental impacts associated with repository implementation;
- Socio-economic aspects: factors contributing to costs and acceptance by all key stakeholders.

As an example, the reference H12 engineered barriers illustrated in Figure 2-3 can be examined in terms of these factors. Referring to options listed in Appendix 1, some areas where design improvements are possible could be:

- Placing several vitrified waste packages in a single overpack. Engineering feasibility should not be greatly influenced as designs containing 2 or 3 containers of HLW are similar in terms of dimensions, weight and thermal loading to particular overpacks studied for the direct disposal of spent fuel (e.g. SKB, 1999; Nagra, 2002). Reduction in the number of emplacement operations could ease engineering practicality and, if the repository could be made more compact, site characterisation requirements and environmental impacts could be reduced. Such variants could reduce costs, but a more rigorous analysis would be needed to ensure that there was no detriment to either long-term or operational safety.

- Prefabricating the main components of the EBS. The difficulty of quality assuring the EBS and, in particular, handling compacted bentonite under high humidity conditions has indicated that prefabricated EBS modules (PEMs) can improve engineering practicality (noted as an option in H12; JNC 2000). SKB and Posiva are testing such a concept at present (Lindgren et al., 2003) and past work in the USA indicates that such designs may also be easier to retrieve (Apted, 1998).
- Selecting designs and materials for secondary engineering structures / barriers (e.g. liners, plugs, grouts) which minimise the risk of perturbations to the primary EBS (NUMO and Posiva, 2004); this contributes to the robustness of the long-term safety case, but potential consequences for operational safety need to be carefully evaluated.
- Variable layouts to make the best use of available host rock; NUMO has already extended the H12 vertical emplacement concept, which considered only a single waste package in a disposal pit, to "multiplex" options in which 2 or 3 packages are stacked in a single pit. In principle, this can be extended further to longer boreholes containing many waste packages or, indeed, deep boreholes drilled from the surface (e.g. SKB, 1992; Deutch et al., 2003). Similarly, horizontal emplacement panels can be stacked to make better use of a thick host rock formation or extended as long tunnels to utilise a formation with limited access (e.g. an underwater formation accessed from land). For very large, multiple waste container overpacks, a cavern disposal option could be considered. Such layout options have clear pros and cons in terms of the design factors above, but a detailed evaluation to allow their direct comparison can only be done on a site-specific basis.

As considered further in the next chapter, details of the design and layout of the underground structures can be specified to take into account the detailed geological environment encountered and the requirements of stakeholders. However, given that operation will commence only in 30 years time and will extend over ~4 decades, it is not sensible to be over-specific about such details at present. It is important that options are kept open to benefit from technical developments over this long period. Nevertheless, it is valuable to consider likely designs appropriate to expected geological environments in order to identify R&D needs and priorities and to initiate discussions with relevant stakeholders.

3 TAILORING A REPOSITORY TO A VOLUNTEER SITE

3.1 Site requirements

For all potential sites, post-closure safety is an absolute requirement which will be continually assessed as the characteristics of the site and the detail of the repository design become better defined (see Chapter 4). Although such assessments are associated with great uncertainties, especially for long times in the future, there are generally accepted methods for carrying these out in a conservative manner. The key characteristic is, however, that levels of safety for a particular concept at a specified site should clearly meet established standards and guidelines.

Unlike the engineered barriers, which will be designed by NUMO, the characteristics of the host rock formations are set by the geology of the volunteer sites. A minimum requirement on the geological environment is that it provides isolation from the dynamic surface environment and physical stability – which together help ensure the longevity of the EBS. The H12 study (JNC, 2000) – in agreement with many studies in other countries (e.g. those shown in Figure 2-2) – has shown that negligible radiological consequences can be assured for geological periods of time for a wide range of different host rock formations. Characteristics of the host rock formations which increase confidence in EBS longevity include mechanical stability, low groundwater fluxes and velocities and geochemical compatibility (for example reducing conditions, near-neutral pH and low salinity).[4]

In addition to providing an environment that ensures good long-term performance of the EBS, the many hundreds of metres of rock between the repository and the biosphere can provide an extremely powerful natural barrier. In some rocks, advective groundwater flow is so low that solute transport is dominated by diffusion processes. In such cases, the migration of most radionuclides from the repository to the surface may be negligibly slow. Even if groundwater flow is more rapid, long transport paths and the interaction of dissolved radionuclides with the solid rock matrix may greatly extend transport times to the biosphere and hence the extent of radioactive decay en route.

In addition to processes which cause delays in release and associated decay of radionuclides, dilution processes should also be considered. Although not commonly regarded as a barrier function, the spreading of releases in time and the dilution of small water fluxes through deep rocks in the larger near-surface or surface water flows tend to further reduce the concentration of radionuclides and hence also their radiological significance.

Favourable geological features – along with other geographical, surface infrastructure and socio-economic aspects – are discussed further as “Favourable Factors” for siting (NUMO, 2004). Already in the Act, some minimum requirements for an acceptable site are specified, with emphasis on long-term geological stability (NUMO, 2004). In terms of the practicality of construction and operation, there are other constraints on a suitable site. In particular from the viewpoint of safety during construction and operation, there are limits to the extent to which difficult construction conditions (e.g. low rock strength, high stress or stress anisotropy, high water inflow, etc.) can be surmounted. Even if safe construction is possible, there may be considerable cost penalties.

[4] N.B.: Host rocks such as salt that are virtually free of groundwater are clearly advantageous here – although they may have their own problems (potential resource, unstable in some perturbation scenarios). In any case, no major deposits of evaporites are found in Japan.

3.2 Illustration of the need for design flexibility

At the first stage of evaluating potential repository concepts at volunteer sites that satisfy the geological stability requirements, NUMO will place particular emphasis on the design factors relating to safety and engineering practicality (see Section 2.3). Criteria specifying minimum levels of practicality and safety will be set for relevant geological formations and, if these are clearly not met, NUMO would reject such a site (Figure 3-1). We thus have no intention of trying to “engineer around” problems at a location which is fundamentally unsuitable for the presently considered disposal technology. We accept that, as technology develops in the future, currently exotic concepts might become practical (e.g. rock melting by very hot waste packages) which could allow such sites to be considered, but such speculative considerations are outwith our present programme.

Given the limited amount of data which may be available at the literature study and PIA characterisation stages, it is possible that a clear decision that a given site is unsuitable cannot be made. If the open questions or uncertainties at a particular site are larger than in other cases, the decision on whether to invest effort in site characterisation work or detailed evaluation of the limits of existing repository technology may be left open until higher priority options have first been examined.

There are also repository design limitations which may be set by the available area of usable rock. Apart from fundamental limitations defined by the extent of the geological formation, there are still uncertainties about what constraints, if any, will be placed on the projected area of the underground repository structures at the surface – termed the “footprint”. Although the legal situation is being investigated, there may be particular boundaries set by the geography of the volunteer community or by specified restricted areas (e.g. national parks, population centres). Together with the structure of potential host formations, this may considerably limit the available area and require consideration of high emplacement density designs.

As indicated by Figure 3-1, there is a lot of flexibility in the concepts which can be assembled from the layouts illustrated in Appendix 1 to respond to even rather severe constraints on the usable volume of rock. At some point, however, if the area is too small – or divided into too many sub-units – to make repository implementation for the target inventory a practical option, we would again reject the site.

Even at this conceptual level, it has to be recognised that design variants have consequences in terms of the repository concept as a whole. For example, high density emplacement options that minimise the repository footprint will inevitably require careful consideration of the effects of increased thermal loading. Again, there are several options to address potential problems – increasing surface storage time prior to disposal, accepting higher temperatures in the EBS, keeping the bentonite dry within a PEM during the time of enhanced temperature or postponing backfilling of the emplacement tunnels (Figure 3-2).

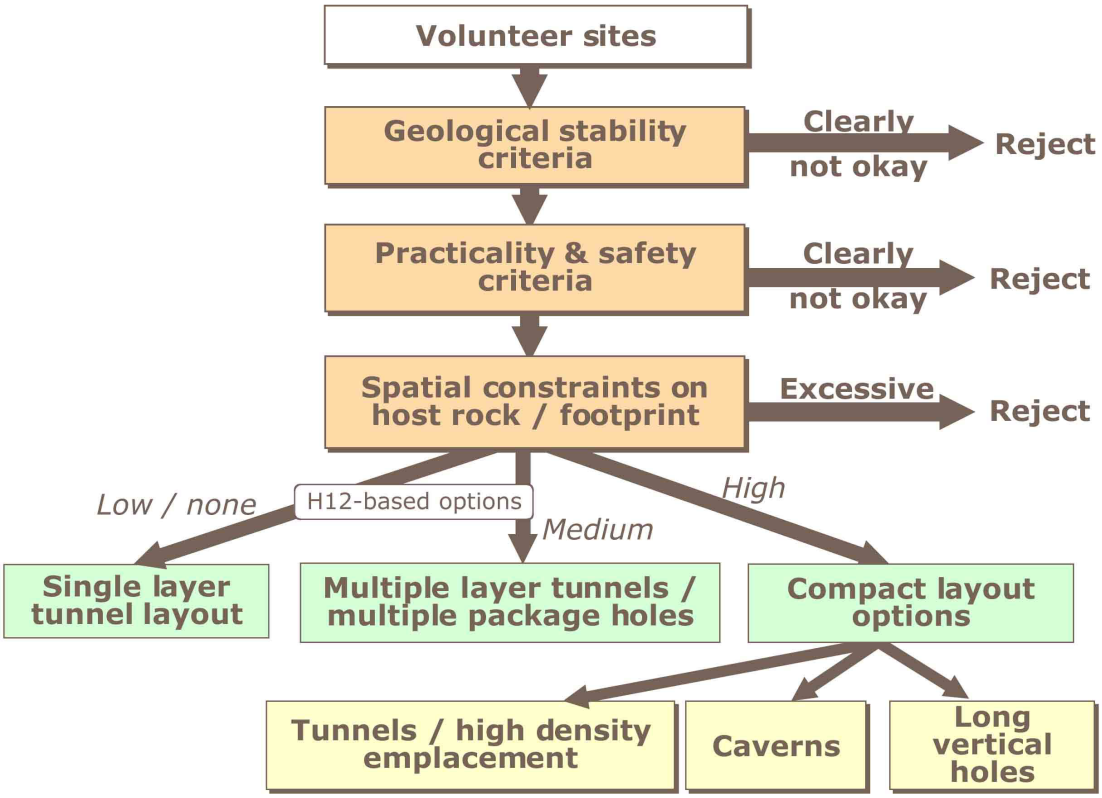

Figure 3-1: Illustration of evaluation of constraints on a site and resultant design variants.

A key factor here is requirements management – ensuring that the justification for choosing any approach is clearly recorded. In this example, if the requirement is specified as keeping bentonite below the very conservative (and rather arbitrary) limit of 100°C set in H12, then the increased surface storage or postponed backfilling options would directly limit the thermal loading and hence the temperature rise in the bentonite. However, if more recent work on the thermal stability of bentonite can be taken into account, then options with a higher maximum temperature requirement - e.g. allowing the thermal loading to increase to 130-150°C - might be acceptable. If the requirement is specifically focused on bentonite stability, credit for yet higher thermal stability of dry bentonite could be accepted at the cost of ensuring that the bentonite can be ensured to remain dry (e.g. PEM shell would have sufficient longevity) under the resultant higher temperature conditions.

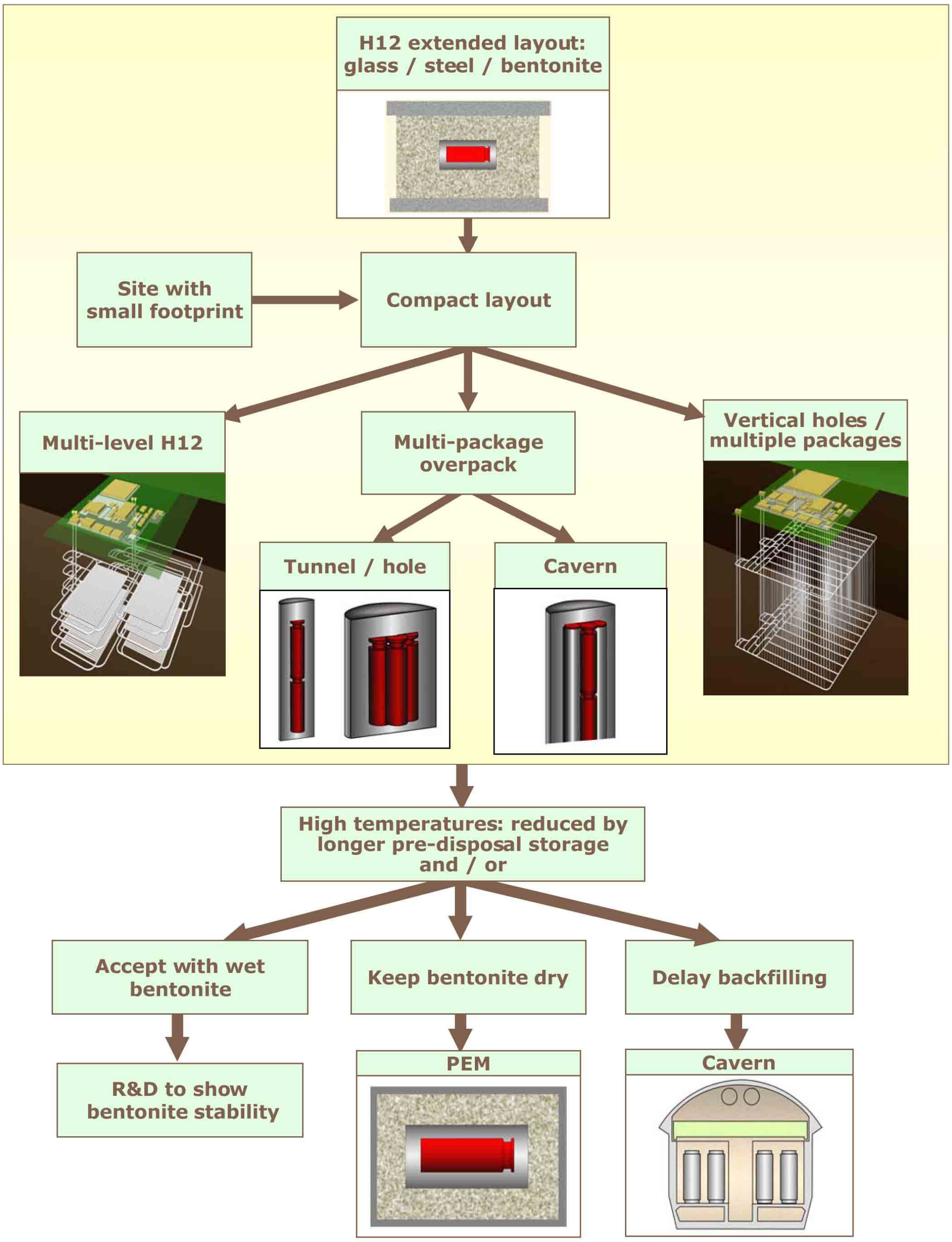

Figure 3-2: Illustration of options which address high thermal loading concerns for compact repository designs.

3.3 Tailoring of repository concepts to site characteristics – a bottom-up approach

As illustrated previously in Figure 1-6, NUMO is carrying out preliminary investigations to examine how generic concepts can be combined with the expected characteristics of potential sites in order to define a set of more site-specific concepts which could be used for detailed performance assessment studies and to determine R&D requirements. In this section a bottom-up approach is briefly described, while in the following section a complementary top-down process is illustrated.

The starting point for the bottom-up approach is the catalogue of repository components (Appendix 1). The aim is to determine the constraints (if any) on any particular component set by the characteristics of a particular site. For the initial studies, only the following geological characteristics of the host formation were considered: rock mechanics, hydrogeology, groundwater chemistry and rock temperature (as determined by emplacement depth and the geothermal gradient).

For each option for repository component or geometrical layout, impacts of the site characteristics on the design factors were evaluated in terms of how the performance of that component in isolation would be affected by changes in these characteristics. Each of these sub-factors (attributes) was then evaluated by a multi-disciplinary expert team with a wide diversity of international experience in repository design, performance assessment and site characterisation.

An abbreviated version of one of the resultant matrices developed by this approach is shown in Figure 3-3. In this particular case, the option of vertical in-hole emplacement of single waste packages (as in H12; JNC, 2000) is examined for a range of possible rock strengths (from hard rock (HR) through increasingly soft rock (SR-A, B, C, D, E), using the classification developed in H12) and hydrogeological conditions, represented by an average hydraulic conductivity (ranging from 10^{-12} to 10^{-8} m s^{-1}).

This compartmentalised approach is somewhat simplistic, but it does force all aspects of a design component to be judged in terms of:

- Whether specific site conditions will be of any significance (if not, noted as not applicable – "n.a.");
- Whether particular parameter ranges would be favourable or unfavourable (triangular profile which is wider for more favourable conditions) ;
- Whether conditions would be problematic (dotted line) or would even "kill" concepts utilising this component (indicated by K).

Open questions are indicated by numbers which relate to a list of comments. The full matrix also includes assessment of the significance of water chemistry (expressed as salinity ranging from "fresh" to "brine") and temperature (over the range 30 – 60°C).

To date, such matrices have been prepared by teams from NUMO and partner organisations, firstly for the key components of the H12 design and, in reduced form (focusing only on safety and engineering design factors), for other components of alternative designs (e.g. various PEM designs). Preliminary work has started on developing "overlays" for the matrices which allow priority areas for consideration to be identified for particular sites, which are characterised by particular combinations of these site characteristics (see Figure 5-2).

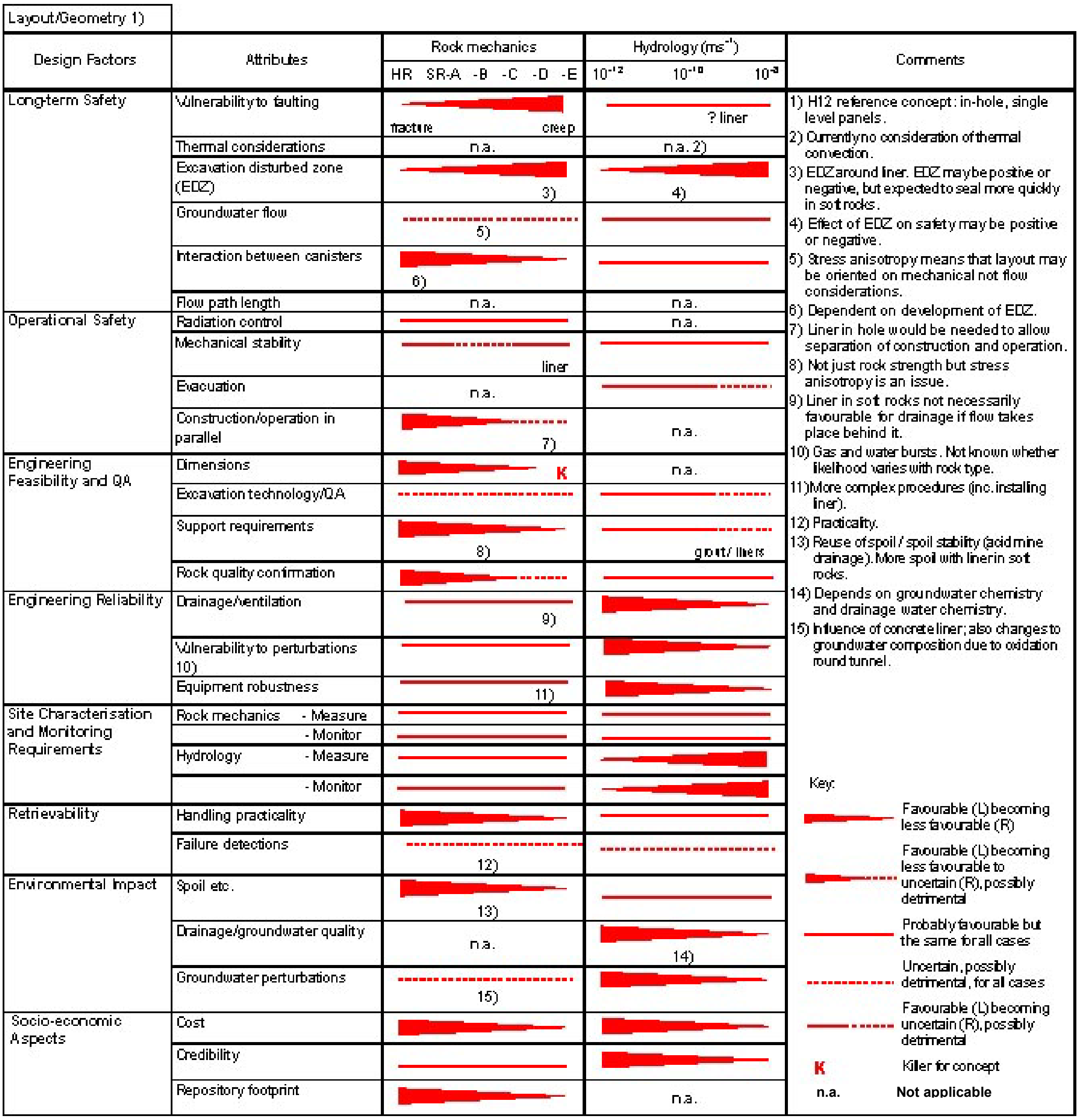

Figure 3-3: Example of a matrix for evaluating the impacts of site characteristics on all of the design factors of relevance for a specific choice of a repository design component (the emplacement layout) (Umeki et al., 2003),

The limitations of this approach have been recognised – in particular the risk of loss of consideration of interfaces and component interactions. In addition, there is a potential for missing key site characteristics, due to the limited number of simple parameter ranges which are used (e.g. rock stress and flow velocity could be more critical rock mechanical / hydrogeological properties in specific cases rather than rock strength and hydraulic conductivity). Further developments to address these issues are planned. Nevertheless, the design matrix approach has proven a very useful tool for bringing together the repository design, performance assessment and site characterisation teams. This is essential in a project which requires intensive interactions of scientists and engineers with diverse areas of responsibility. It should also be emphasised that, even at this initial stage, environmental and socio-economic factors are explicitly included, to ensure that these critical aspects are borne in mind by all those involved.

3.4 Matching repository concepts to site characteristics – a top-down approach

A complementary approach to that illustrated above analysed a) the feasibility or suitability of a simplified H12 "generic repository" in different siting environments and b) the suitability of different repository concepts for a simplified "generic site". These two exercises serve as a preparation for the later comparison of different site-specific repository concepts.

In the first case, eight "Potential Siting Environments" (PSEs) were defined (Figure 3-4) which were considered reasonably representative of the types of geological situations that can be found in Japan (see also NUMO, 2004). These can be associated with typical geographical settings where such environments are encountered in order to develop a series of study cases.

The pros and cons of the different PSEs as potential hosts for an H12 type repository were identified, allowing them to be compared with each other. A multi-attribute analysis (MAA) approach was used for this complex, multi-dimensional problem. Since the geological data assumed were very broad, little distinction could be made amongst the expected long term safety performance of the sites. The focus for the initial exercise was therefore on practicality and cost of implementation and likely extent of public support and hence key attributes of the sites included topography and transportation infrastructure.

The same MAA approach was used in the second exercise to gain experience in the ranking of different repository concepts for a specific site. Two different host rocks were considered (crystalline and hard sediment) and outline repository concepts derived from key components from the components catalogue (Appendix 1). The characteristics of these cases were:

A – H12 single-level layout with vertical EBS constructed in-situ;

B – H12 single-level layout with horizontal EBS constructed in-situ;

C – H12 multi-level layout with horizontal EBS constructed in-situ;

D – Very deep borehole emplacement (3-5 km below surface) with no buffer;

E – Emplacement of PEMs in mined boreholes (300-800m below surface);

F – Emplacement of PEMs in long horizontal tunnels;

G – Emplacement of casks containing 20 waste packages in caverns (with delayed backfilling).

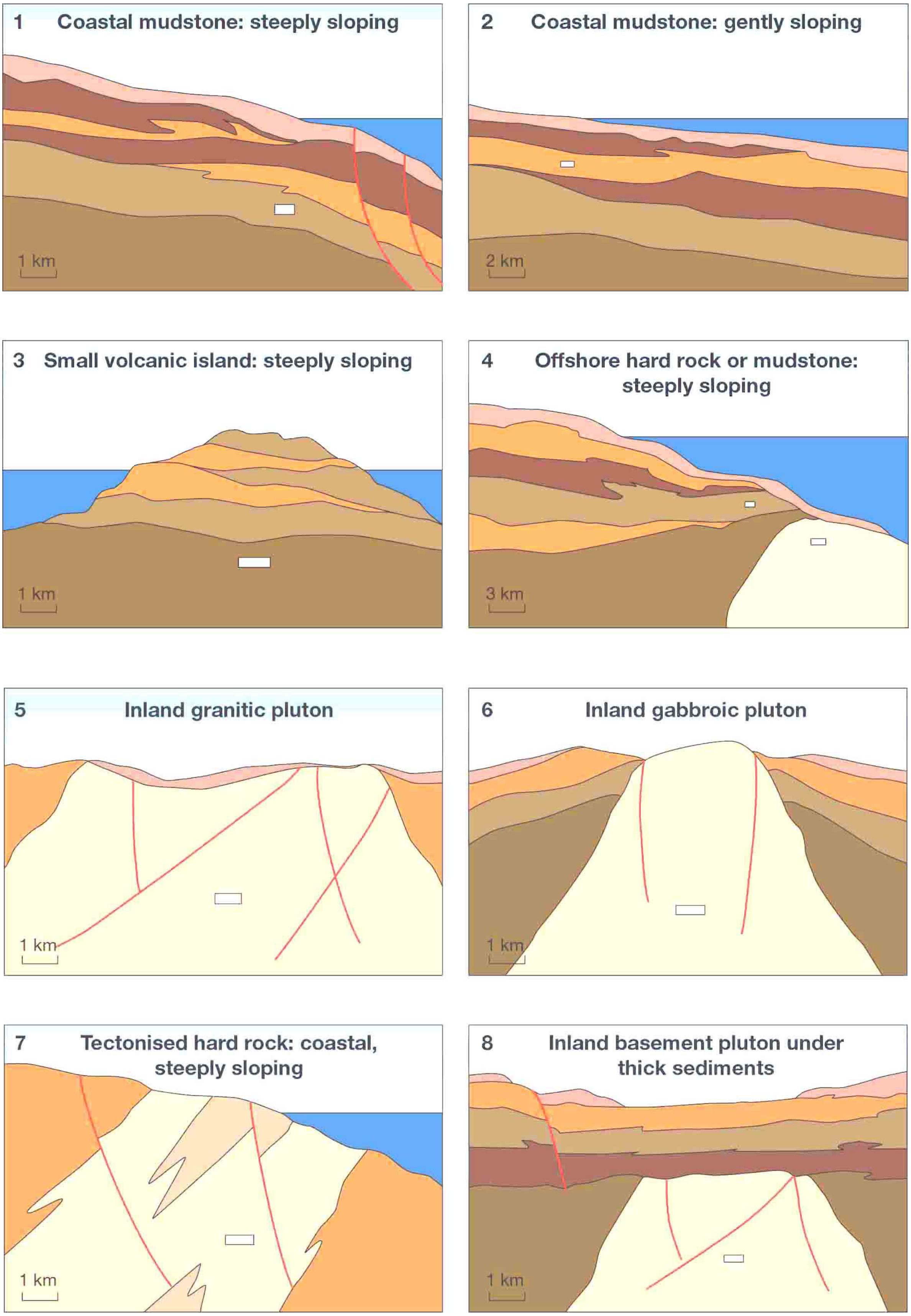

Figure 3-4: Potential siting environments for the MAA exercise (vertical scale exaggerated; repository not precisely scaled).

This study highlighted some of the main differences between these options, but also some of the difficulties which result from the uneven level of understanding of different concepts (tending to lead to more favourable ranking of less well studied options). Even on the basis of rather simple preliminary analyses, it was clear that the subjective weightings placed by different stakeholders on the various site or concept attributes could significantly alter the resultant ranking. Nevertheless, the increased system understanding and improved interaction between different technical groups within NUMO has shown these exercises to be extremely valuable.

In the future, MAA could potentially also help to develop transparent and traceable documentation for this ranking process. However, it has been seen that results from such studies are often hard to communicate to persons not directly involved in the discussions on scoring and weighting attributes.

3.5 Tailoring of repository concepts - involvement of stakeholders

As noted in the previous section, the MAA approach involves consideration of a range of socio-economic factors. Because of the flexibility of the MAA software used, it is relatively easy to examine the effects of the changing weighting of different attributes (e.g. "public acceptance" or "cost") in order to reflect the concerns of different stakeholder groups. Ideally, when volunteers come forward, stakeholders could take part directly in such concept and site comparison exercises. For example, we hope to involve key stakeholders – and in particular local communities – in the process of defining some of the attributes to be considered and their associated weightings.

In general terms, there are a number of decision points where external input will play a role. We plan for a stepwise technical development of the repository concept with iterative input from, and output to, the site characterisation work. It is also intended to solicit input from the public, with particular emphasis on the areas which are of most concern to them and where they can contribute most. In addition, we will involve other key groups of stakeholders in the decision process – particularly for more technical aspects (e.g. university professors, professional societies such as JSCE[5], AESJ[6]).

Although the principles are easy to list, we appreciate that some of the choices to be made in repository concept development involve rather complex considerations. For example, many groups consider ease of retrieval and delayed closure of the repository as a positive feature which maximises the time available to make decisions and allows future generations to choose the ultimate concept and disposal strategy. On the other hand, from the point of view of security and long-term performance of the engineered barriers, it is desirable to seal the repository as rapidly as possible and make waste retrieval as difficult as possible. Balancing these conflicting objectives involves both technical and ethical issues and we would hope to develop consensus on such issues with all interested parties.

[5] JSCE: Japan Society of Civil Engineers (http://www.jsce-int.org).
[6] AESJ: Atomic Energy Society of Japan (http://wwwsoc.nii.ac.jp/aesj/index-e.html).

Box 2
Reversibility and Retrievability

Reversibility: Denotes the ability to reverse one or a series of steps in repository planning and development, at any particular stage of the programme. This implies being prepared to review, and if necessary re-evaluate, earlier decisions, as well as maintaining the technical means to reverse a step. A programme may be planned to facilitate reversibility, for example by adopting small steps and frequent reviews in the programme, as well as by implementing specific engineering measures. Reversibility provides flexibility in the programme and can thus allow stakeholders to participate more actively in decision-making at each step. In the early stages of a programme, reversal of a decision regarding site qualification, or the adoption of a particular design option, may be considered. At later stages, during construction and operation, or following emplacement of the waste, reversal may involve engineering measures, such as the modification of one or more components, or even retrieval of waste packages.

Retrievability: This is a special case of reversibility, being the ability to reverse the action of waste emplacement. Retrieval, the action of recovery of waste or waste packages, may be considered at various stages after emplacement. In discussing retrievability, it is important to specify what is to be retrieved, since this affects the implementation and technical feasibility. Retrieval could, for example, refer to recovery of individual waste packages, identified as faulty or damaged, even as emplacement of other packages continues, recovery of some or all of the waste packages at some time after emplacement, or excavation of the waste materials in the far future, when the packages are no longer intact. Retrievability may be facilitated by the repository design and operational strategies, e.g. by leaving underground access ways open and emplacement / retrieval systems in place until a late stage, or through the development and use of durable containers and easily excavated backfill.

4 ENSURING SAFETY

4.1 The importance of safety and confidence-building

Safety is the top priority for NUMO in its development of HLW repository concepts. This applies to all the conventional activities associated with construction, operation, monitoring, closure and decommissioning of all waste management facilities, all operations involving transportation and handling of radioactive materials and the long-term behaviour of the repository after it is finally closed and sealed. We expect rigorous overview from independent regulatory authorities up to the point of closure and realise that we must be able to clearly demonstrate compliance with all relevant regulations and guidelines. In order to do so, there will be an iterative evaluation of safety throughout our development of repository concepts. In fact, this has already started and will continue up to and throughout the implementation phase; the present chapter, together with Appendix 2, therefore lays out the basic safety-relevant issues and explains the specialist terminology involved.

In order to promote safety consciousness, we have identified establishing a "Safety Culture" as one of our primary goals. For NUMO, the fundamental aspect of a safety culture is that all staff accept and practice an active commitment to ensuring that safety has priority over all other issues. This culture must permeate all activities – and we have recognised that it can be most easily established in a new company during the time when the basic "company culture" is evolving. Nevertheless, the safety culture needs to be actively developed and then continuously reinforced, with special consideration of each new generation of staff.

The importance of such a safety culture has been explicitly accepted at all hierarchical management levels in NUMO (and, as with the "quality culture", will be extended to all key external contractors and suppliers). It is recognised to apply to all activities within a project – from first planning through implementation to completion and final decommissioning.

A specific aspect of maintaining a safety culture concerns the development of appropriate guidelines for quality assurance (QA) or, more generally, quality management (QM). This is an important general requirement for all nuclear facilities and is a component of the measures needed to build confidence in the safety of the repository (see below). QM is a formal, systematic approach to ensuring that a project is planned and implemented to meet clearly defined goals. As noted above, the most critical goal is safety; in the case of a repository, this includes not only safety during the construction and operational phases but also the less tangible post-closure safety over geological time periods.

Demonstrating safety during this very long post-closure phase poses one of the greatest challenges in repository programmes. The set of arguments used to address this task is often labelled "the safety case" (see Box 3). Long-term safety is based on the functioning of a suite of engineered barriers within a natural barrier system. It is essential, therefore, that the engineered structures are always emplaced rigorously according to specifications and that previous or subsequent repository operations do not perturb the barrier roles of the geosphere. To achieve these goals, we intend the QM system to be designed, implemented and further developed iteratively by a multidisciplinary team including those responsible for site characterisation, for design and operation of the facilities and for performance assessment. In addition, further goals for the QM system are associated with cost, timescales, environmental impact and, in particular, social acceptance.

The H12 project (JNC, 2000) already focused on evaluating post-closure safety and did this by using a simple, conservative approach for generic site conditions. In order to fulfil the expanded requirements when dealing with a range of repository concepts and with a variety of volunteer sites, major extension of this background is required. We must be in a position to:

- Evaluate safety during construction and operation of the repository (considering both conventional and radiological hazards);
- Evaluate post-closure performance more realistically, in order to identify differences between different concepts and different sites;
- Provide the documentation required for licensing procedures;
- Identify requirements for, or pros / cons of, monitoring and institutional control options;
- Facilitate communication within NUMO (in particular technical groups involved in site characterisation and repository design) and with other stakeholders.

Appendix 2 provides an overview of post-closure safety assessment methodology and a summary of key results from H12. The following sections of this chapter consider each of the first four points above. The fifth point is a global aim and is explicitly addressed within each of these sections. In the following box, some of the key concepts involved are introduced and the terminology used by NUMO is defined.

Box 3
Safety in Geological Disposal: Concepts and Definitions

In geological disposal, the overriding goal is to ensure that humans and the environment are protected at all times from harmful effects. This has resulted in the development of numerous repository-specific safety issues and of corresponding terminology. These are summarised and defined here.

The entire undertaking of implementing a geological repository should be governed by a strong *safety culture.* This culture is maintained, in part, by having an efficient quality management system, which includes technical quality assurance or quality control elements. Analyses of safety are often divided into *operational phase safety* and *post-closure safety*. Because of the long timescales involved, most discussion has centred on the latter and a structured approach to demonstrating long-term safety has been developed. This is based upon a sound safety strategy that allows establishment of a *safety case* that is *robust.* One important element of the safety case is quantitative *performance assessment* or *safety assessment*. A further important element of the safety case is a statement of *confidence*. For clarity the italicised terms are defined below.

Safety culture: The assembly of characteristics and attitudes in organisations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance.

Operational phase safety: Conventional and radiological safety during construction and all of the period where the repository is open for waste emplacement or for inspection.

Post-closure safety: Radiological safety in the period after the facility is closed and sealed.

Safety case: A safety case is a collection of arguments in support of the safety of the repository and is developed for both the operational and post-closure phases. A safety case comprises the findings of a safety assessment and a statement of confidence in these findings. It should acknowledge the existence of any unresolved issues and provide guidance for work to resolve these issues in future development stages. For social acceptance, it is critical not only to make a technical safety case, but also to explain it to key stakeholders.

Robust: A robust repository system is based on (1) sites with well-defined and favourable conditions and a well designed repository; (2) sufficiently large safety factors; and (3) some degree of redundancy. A robust performance assessment is characterised by (1) being based either on well understood, realistic models or else on clearly conservative models and data; (2) assuring that all potentially negative processes are analysed; and (3) being relatively insensitive to parameter and conceptual model uncertainties.

Performance assessment: An assessment of the performance of a system or subsystem and its implications for protection and safety at a planned or an authorised facility. This differs from safety assessment in that it can be applied to parts of a facility, and does not necessarily require assessment of radiological impacts.

Safety assessment: An analysis to evaluate the performance of an overall system and its impact, where the performance measure is radiological impact or some other global measure of impact on safety.

Confidence: Confidence results from a positive judgement by all key stakeholders that a given set of conclusions is well supported. Confidence is based not only on the safety case, but also on the perceived credibility of all organisations involved (especially the implementer and regulators).

These definitions are based largely on accepted international usage as recorded in the documentation of the NEA and the IAEA (NEA, 1999a; IAEA, 2003).

4.2 Special safety concerns during construction and operation

As pointed out above, most attention in repository programmes in their early phases has been directed towards the assessment of long-term safety. As concepts become firmer and one moves towards realisation of facilities, the importance of the construction and operational phases grows. Compared to evaluation of performance over geological periods of time, assessment of operational safety utilises more conventional methodology. Detailed planning of construction and operation activities includes an assessment of the risks and consequences of various incidents, accidents and perturbations. Many well-established techniques exist for such assessment (e.g. fault trees, event trees) and their implementation can be facilitated by using computer-aided design (CAD) tools which allow an advance “walk-through” of all such activities. These analyses can feed back to allow decisions to be made about design variants (e.g. shaft vs. ramp access, horizontal vs. vertical emplacement), design details (e.g. liner material / thickness, use of rock bolts / anchors) or operational variants (e.g. extent of remote handling, number of back-up electrical generators).

A particular challenge may arise when the requirements for operational safety give rise to a conflict with either post-closure safety requirements or with socio-economic wishes. A typical example of the former could involve use of cement / concrete for grouting, tunnel lining, etc. (NUMO and Posiva, 2004). Construction engineers may desire extensive use of this well-known material to minimise difficulties (and hence risks) of construction activities. The long-term performance assessors, on the other hand, may want to avoid or minimise the chemical complexities associated with hyperalkaline leachates from cementitious materials.

An example of the latter conflict involving socio-economic constraints might result from a desire of local communities to keep waste accessible for easy inspection for a long time, conflicting with the engineers' preference of sealing underground openings as quickly as possible (see also Section 3.5).

In any case, NUMO plans iterative development of design, with active involvement of all interested expert groups, to ensure that optimal solutions are produced. At present, including operational safety as a design factor considered in both the bottom-up and top-down concept development studies allows key issues to be identified (Chapter 3). In order to go further – and in particular to compare different concepts and sites – a more quantitative approach is required.

Like long-term safety assessment (Appendix 2), a starting point for quantitative analysis of operational safety involves scenario development. As noted previously in the design principles (Chapter 2), pre-emptive planning attempts to identify possible perturbations that may occur during construction and operation of the repository. This is made easier by aiming for simplicity and a robust design. Wherever possible, designs and procedures will be modified to avoid potential hazards. However, some perturbing processes will not be able to be completely excluded – even if they are unlikely.

Two categories of perturbation can be identified – major disturbances associated with events which affect many aspects of construction and operation simultaneously (e.g. a major earthquake) and minor events which affect only a single operation (e.g. failures of a single piece of equipment). As the former are generally of more concern, they are the focus for NUMO's initial studies. Nevertheless, studies have already been initiated in Japan to determine the robustness of operational equipment, with emphasis on remotely operated systems (Masuda et al., 2004).

For relevant scenarios, methodologies are being developed to estimate the probability of disturbances and then calculate their consequences. An aim is to be able to estimate probabilities and consequences in both a conservative manner (to determine compliance with guidelines) and also as realistically as possible (in order to identify differences between specific sites and repository concepts).

4.3 Quantitative analysis methods for realistic assessment of long-term safety

As discussed above for operational safety, conservative quantitative analysis to assess repository safety is required to demonstrate compliance with regulatory guidelines (Appendix 2). A problem with such an approach is that the simplification required is often so great that the analysis is completely insensitive to even rather major variations in site and repository concept properties. The H12 study, for example, showed the potential for a number of different EBS designs to meet typical regulatory guidelines, but could not quantitatively discriminate between the safety levels for a case of vertical emplacement with a plug and large, lined overlying tunnel and a case of horizontal emplacement in an unlined tunnel.

For any specific repository design in a particular siting environment, many different features, events and processes (FEPs) can influence the isolation of radionuclides. These can be represented in a set of scenarios of the type developed in the H12 project (JNC, 2000; Appendix 2). A challenge is to move on from these static, generic scenarios (Figure 4-1). The aim is to better represent varying slow evolution / degradation of the repository barriers for different concepts and sites - i.e. rather than examining the different scenarios indicated in Figure 4-1 as alternative systems, considering directly the changes from the fixed starting point at time of closure (A and B) to produce different future conditions (e.g. A1 – A4, B1, B2). These should also identify clearly the inherent uncertainties involved and major perturbations which can disrupt one or more barriers (due to natural or anthropogenic events).

Representations of potential evolution scenarios, even if rather unlikely, should be distinguished from "What if?" scenarios. The latter can involve physically impossible assumptions (e.g. disappearing canisters, direct transport of radionuclides from the EBS to the biosphere), which can be used to improve understanding of system behaviour and help explain some aspects of the safety case (e.g. the multi-barrier system), but do not represent any kind of evaluation of possible system evolution. Hence, even if analysed by the same quantitative tools, it is important to separate these in the discussion of repository performance.

In some cases, regulations in foreign countries specify separate treatment of other special groups of scenarios – in particular those associated with future human actions. Although such regulations are not yet defined in Japan, special treatment of human intrusion scenarios seems sensible and these will be considered carefully by NUMO.

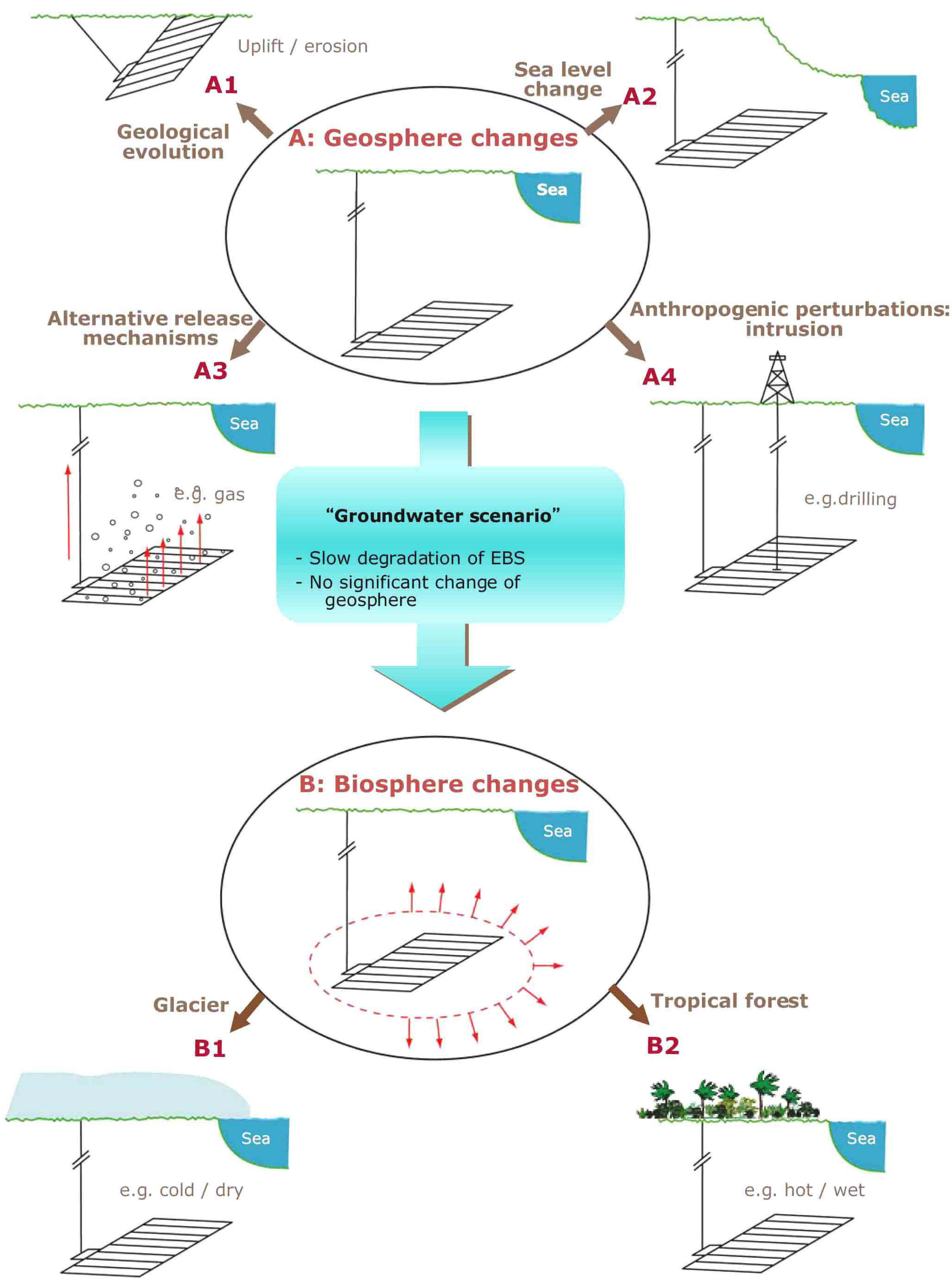

Figure 4-1: Development of scenarios to describe possible future evolution of a deep geological repository.

In addition to improving the scenario development process, NUMO intends to further develop the models and databases established by JNC for quantitative consequence analysis (JNC, 2000; Appendix 2). Specific aims include:

- More realistically representing the geometry of all components of the engineered barriers (essential for distinguishing between different repository design options);
- Including explicit representation of all materials present in the repository engineered structures and considering any significant interactions between them;
- Realistically representing the 3D geometry of the geosphere, with particular emphasis on the solute transport characteristics of all relevant formations;
- Developing a model of a Japan-specific biosphere which contains appropriate diet and lifestyle information and improved representation of the geosphere / biosphere interface for inland and coastal conditions;
- Incorporation of time dependency into the model chain in order to evaluate scenarios which evolve gradually with time;
- Improved assessment of uncertainties and their development in time and space;
- Increased efforts to test (verify and validate) models and databases;
- Development of presentation formats to make results understandable to a wider audience.

These intended developments will, of course, be coordinated with parallel efforts in the international safety assessment community.

4.4 Making and documenting the safety case

In the staged repository implementation programme, we envisage several formal licensing steps associated with site selection and subsequent repository construction, operation and closure. At each of these, a safety case would be presented which would become more detailed as the characteristics of the site and the design of the repository become better defined. As noted in Box 3, the safety case (for both operational and post-closure phases) would include a series of more general arguments in addition to a quantitative safety assessment. A further important component of the licensing documentation will be a quality assured documentation trail which ensures that the assumptions, data and models supporting the safety case are fully transparent and reproducible. The importance of QM was emphasised in Section 4.1 above and the documentation of assumptions will be facilitated by the requirements management process, supporting repository concept development and drawing together the decision process developed in the top-down and bottom-up studies (Chapter 3).

It is also to be expected that key safety documents will be subjected to peer review by independent national and international groups. For the latter, we plan that key documents will be produced in English. Experience has already been gained in this area during the positive review of H12 by the NEA (NEA, 1999b). Indeed, for the production of important documents, NUMO has already established domestic and international expert groups which serve as internal advisory and review bodies. The deliberations of NUMO's International Technical

Advisory Committee (ITAC) are summarised on our English language website (http://www.numo.or.jp/english/index.html)

4.5 Monitoring and institutional control

We aim to establish a monitoring programme to ensure that all operations are carried out safely, with no detrimental impact on the environment and that the as-built repository meets the quality requirements for ensuring long-term safety.

Box 4
Monitoring, Control, Demonstration and Performance Confirmation

Raising confidence in the safety of a repository is a continuing challenge that can lead to a range of specific activities during the repository development, operation and post-closure phases. The behaviour of the repository system is *monitored* throughout its lifetime. Special experiments or measurement programmes may be introduced as *demonstration activities* or else as *confirmation* that the repository is performing as expected. After closure, passive and active *institutional controls* reduce the probability of inadvertent intrusion. For clarity the italicised terms are defined here (IAEA, 2001).

Monitoring: The measurement of radiological or non-radiological parameters for reasons related to the assessment or control of exposure and environmental impacts, and to the interpretation of such measurements. Monitoring can be continuous or sporadic.

Demonstration activities: Activities may be performed by the implementer to illustrate – in particular to other stakeholders and the public - that the chosen repository designs and operating modes do indeed perform as expected. Direct demonstration of long-term post-closure safety is, of course, not feasible. Demonstration facilities may be a part of the main disposal area or may be in separate – but still representative - areas to allow intensive monitoring without compromising the integrity of the repository.

Performance confirmation: The performance confirmation programme is a process to test and evaluate whether the repository system is working as expected and within an acceptable safety margin. The tests and evaluations must be based on observations of changes in natural and engineered systems and components (i.e. monitoring). Monitoring provides one basis for performance confirmation because it delivers data representing direct and indirect observations of the natural and engineered systems that comprise the geological repository. Scientific analysis of monitoring data provides the second basis for performance confirmation, as it is the process by which observed behaviour will be compared with that expected and the significance of deviations evaluated.

Institutional control: Control of a waste site by an authority or institution designated under the laws of a country or state. This control may be active (monitoring, surveillance, remedial work) or passive (land use control) and may be a factor in the design of a nuclear facility (e.g. near-surface disposal facility).

In developing a monitoring programme, the aims to be considered include:

- Assessing site perturbation due to the presence of the repository;
- Assuring operational safety and performance;
- Responding to unlikely perturbation scenarios during the operational phase;
- Collecting data for model and database confirmation or to support operational phase decisions;
- Meeting regulatory requirements;
- Building confidence on the part of stakeholders and the general public.

Considering the aims listed above in turn, the programme requirements for each can be outlined. In general, the requirements are additive – going down the list involves further work, but also utilises the information and resources from those above.

Any major construction activity will inevitably perturb the local environment. An associated environmental impact assessment (EIA) will evaluate all potential disturbances of the "environment" – e.g. air & water quality, land use and appearance, biological diversity, economic impact, traffic. We will continuously monitor such effects during repository construction and operation and will ensure that comprehensive "baseline" measurements of all relevant parameters are made prior to commencing the project, so that influences due to the repository can be distinguished from natural fluctuations (see also NUMO, 2004). Such baseline measurements will be initiated at the start of field work (PIA stage) and hence will be directly considered when planning site characterisation programmes for volunteers.

The operational requirements for safety and quality monitoring in a repository are well established, based on experience in the nuclear and underground construction industries. As yet, however, there is limited practical experience in combining these in a single facility and hence we identify this as an area for future R&D.

During expected operations there would be no release of radioactivity from the waste packages to the environment (although there will be an inevitable release of natural radioactivity due to underground construction activities – as occurs in all such work). Nevertheless, certain accidents (e.g. package drop, fire, explosion) or natural events (e.g. earthquake, tsunami) could potentially give rise to a release of radioactivity. A monitoring network is needed to indicate whether such releases have, in fact, occurred, to assess the consequences of these releases and to guide remediation activities. In principle, the requirements are similar to those for other nuclear facilities, but the monitoring network has to reflect the facilities and scenarios involved.

The safety case for the post-closure phase of the repository incorporates a logical set of arguments supported by analyses carried out by a suite of mathematical models. As construction and operation activities progress, there are opportunities to test the predictive abilities of the codes and data involved using site-specific measurements. Some tests are fairly conventional and can utilise data from some of the monitoring which would be required for the purposes considered above. Tests of the engineered barriers (and the surrounding geosphere) are much more difficult to devise without risking negative influences on repository performance. Such tests may be carried out at a separate location, where performance can be examined by "post-mortem" excavation. If required, a special "performance confirmation" facility could be situated within the repository area.

Regulations for HLW disposal are not yet specified, but information needed for conventional EIA and operational safety aspects should be provided by the systems discussed above. The regulators may, however, desire to test the performance of the "as-built" facility; for example by monitoring of the quality of the EBS and assessing its rate of degradation *in-situ*.

We consider it essential to demonstrate the safety of the repository to stakeholders and this may require very gradual staging of decisions with extensive monitoring of emplaced waste and even "inspectability" for an extended period. Delayed backfilling can allow such inspectability, but is practical only for few of the repository design options presented in Appendix 1. Such options are inevitably associated with risks to workers during the institutional control period and of degradation of long-term performance. Hence, these options need to very carefully consider such issues. Alternatively, a demonstration facility can be constructed elsewhere within the site; it is possible that some technical concepts can be demonstrated without use of real waste.

Any design which includes keeping underground structures open for an extended period of monitoring / inspection will inevitably be associated with a number of issues, including:

- More extensive perturbation of site characteristics (hydrogeology, geochemistry, etc.) and potential degradation of the geological barrier;
- Inevitable degradation of structures (e.g. cracking of liners) with possible requirements for maintenance / repair;
- Risk of accidents (e.g. loss of services leading to flooding or gas explosion) or deliberate intrusion;
- Risk of abandonment / incomplete sealing (e.g. as a result of social disruptions);
- Requirement to maintain an experienced workforce over long periods.

We will openly discuss such points with local communities, and need to clearly communicate that:

- Monitoring is not required to achieve safety; the passive safety barriers and the active measures taken during operation do this. It is simply a check that all is in order;
- Monitoring can be as extensive in scope and continue for as long as future society wishes, but it should not result in significant negative effects on safety and it is our job to ensure this (if necessary, modifying designs to comply with societal demands).

5 DEVELOPMENT OF THE R&D PROGRAMME TO SUPPORT REPOSITORY CONCEPT DEVELOPMENT

5.1 Setting goals and priorities

As indicated previously in Figure 1-6, the R&D to support repository concept development will evolve in response to progress in the site characterisation work. As discussed in Chapter 3, at NUMO we have established a structured procedure for developing repository concepts suitable for volunteer sites in a staged manner. This is strongly coupled to assessment of operational and post-closure safety (Chapter 4). The interactions and data flows between these two work areas are illustrated in Figure 5-1. In both Chapters 3 and 4, requirements for future R&D have been identified. The challenge is to derive an overall structured R&D programme which provides the input needed for particular milestones in an efficient and cost-effective manner.

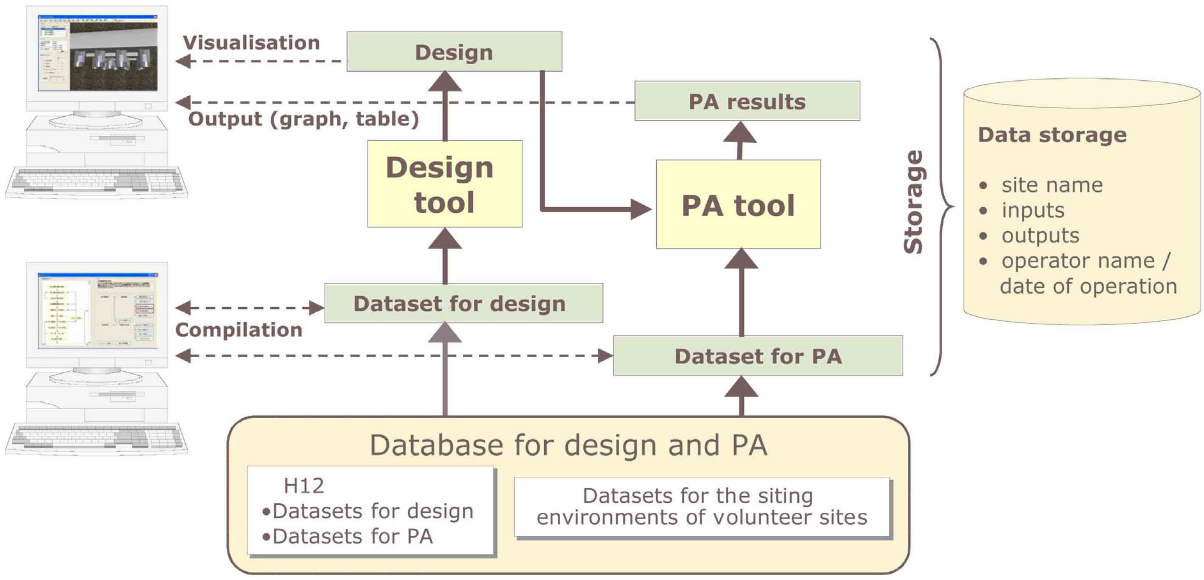

Figure 5-1: Coupling of information flow between repository design and performance assessment (PA) work areas.

Box 5
Terminology: R&D and D&V

In the Japanese programme, the term research and development (R&D) is used to include all work aimed at building fundamental scientific understanding and establishing necessary technology. Demonstration and validation (D&V) refers to work which confirms that the resultant tools, models and engineering concepts are practical and builds the confidence needed for implementation, licensing and public acceptance. Although these areas are often separated, to ease discussion we will consider the latter as a sub-set of the former.

The process of defining an R&D programme is ongoing at NUMO; this is needed both for providing the basis for repository concept development (Section 5.2) and for the assessment of volunteer sites (Section 5.3). It involves establishing a list of important open questions, which is complicated at the present programme stage when a wide range of design options is under consideration. To help, NUMO has developed an approach in which the requirements on individual components of repository designs are evaluated for the range of conditions expected at potential sites ("bottom-up approach", Section 3.3). The matrices which are used to identify site-specific constraints (Figure 3-3) can be extended to more clearly identify and prioritise specific open questions and the approaches to addressing these (Figure 5-2). The very specific open questions are complemented by larger issues raised by the "top-down" approach (Section 3.4).

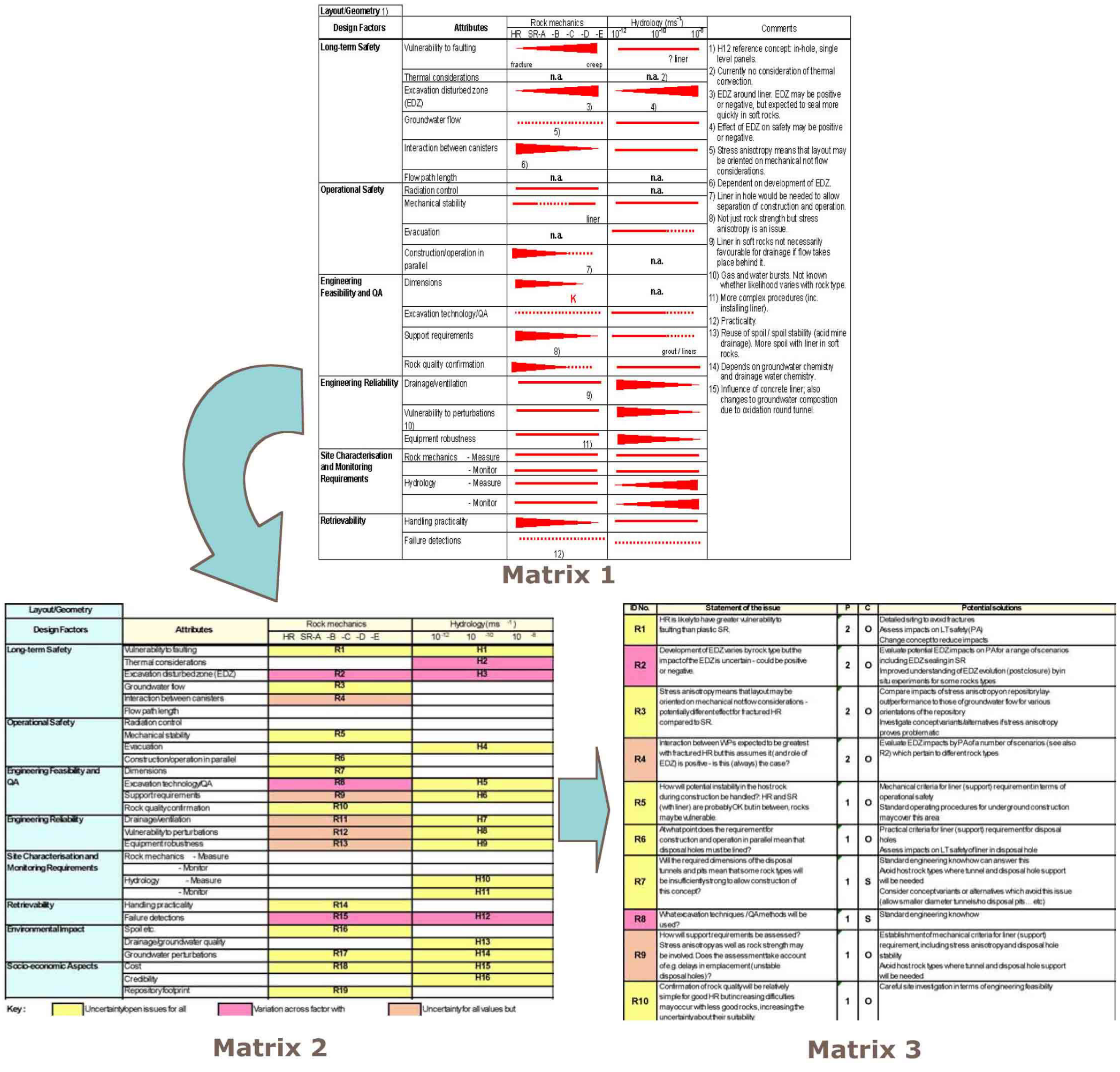

Figure 5-2: Example of use of the matrix overlay approach to identify and classify open issues (Umeki et al., 2003; Ueda et al., 2004).

The generic evaluation of a component (Matrix 1), as presented earlier in Figure 3-3, can be extended to consider the specific conditions in a particular PSE (Figure 3-4) or volunteer site. The resultant "overlay" (Matrix 2) highlights and classifies site-specific issues. These open issues are then expanded in Matrix 3 to identify R&D requirements and give some indication of relative priorities.

With the starting point of a list derived from such work, priorities can be set for work to be performed in the following three areas currently of relevance for NUMO's development of repository concepts:

- Preliminary work required urgently to establish the basis for developing repository concepts from the components catalogue (Appendix 1) and assessing them in terms of the established design factors (Figure 1-6);
- Preparation for the evaluation over the next few years of volunteer sites on the basis of literature studies;
- Longer term work which requires special consideration due to the need for:
  - Establishing NUMO credibility;
  - Building up experience in NUMO teams;
  - Long time baselines;
  - Preservation of expertise in Japanese expert teams;
  - Obtaining maximum benefit from collaborative work with partner organisations.

These are considered further in the following sections. It may be noted that there is some inevitable overlap with the R&D work that is more directly related to site selection and characterisation.

5.2 R&D to provide the basis for repository concept development

Until volunteers come forward, the procedure for developing site-specific repository concepts will be advanced by further iterations of the work described in Chapters 3 and 4, using increasingly detailed specifications of the PSE. In order to compare different RDOs, a clear need has been identified for bringing assessment of key components to a similar level. This involves fundamental design studies with associated scoping analysis of basic constraints (e.g. rock mechanics, thermal analysis) and post-closure safety. A modelling toolkit for such work exists (Figure 5-3), but improvements are planned to allow differences between RDOs / sites to be assessed more rigorously. Development of a methodology for scoping assessments of operational safety is also a priority.

As illustrated in Appendix 1, the different repository concepts considered have a number of common features, including:

- Surface facilities for waste reception, packaging, handling, administration, security, etc.;
- Access tunnels or shafts;
- Underground tunnels, holes or caverns for waste emplacement;
- Robust overpacks for HLW;
- Backfilling, sealing and plugging systems;
- Service facilities for ventilation, drainage, etc.

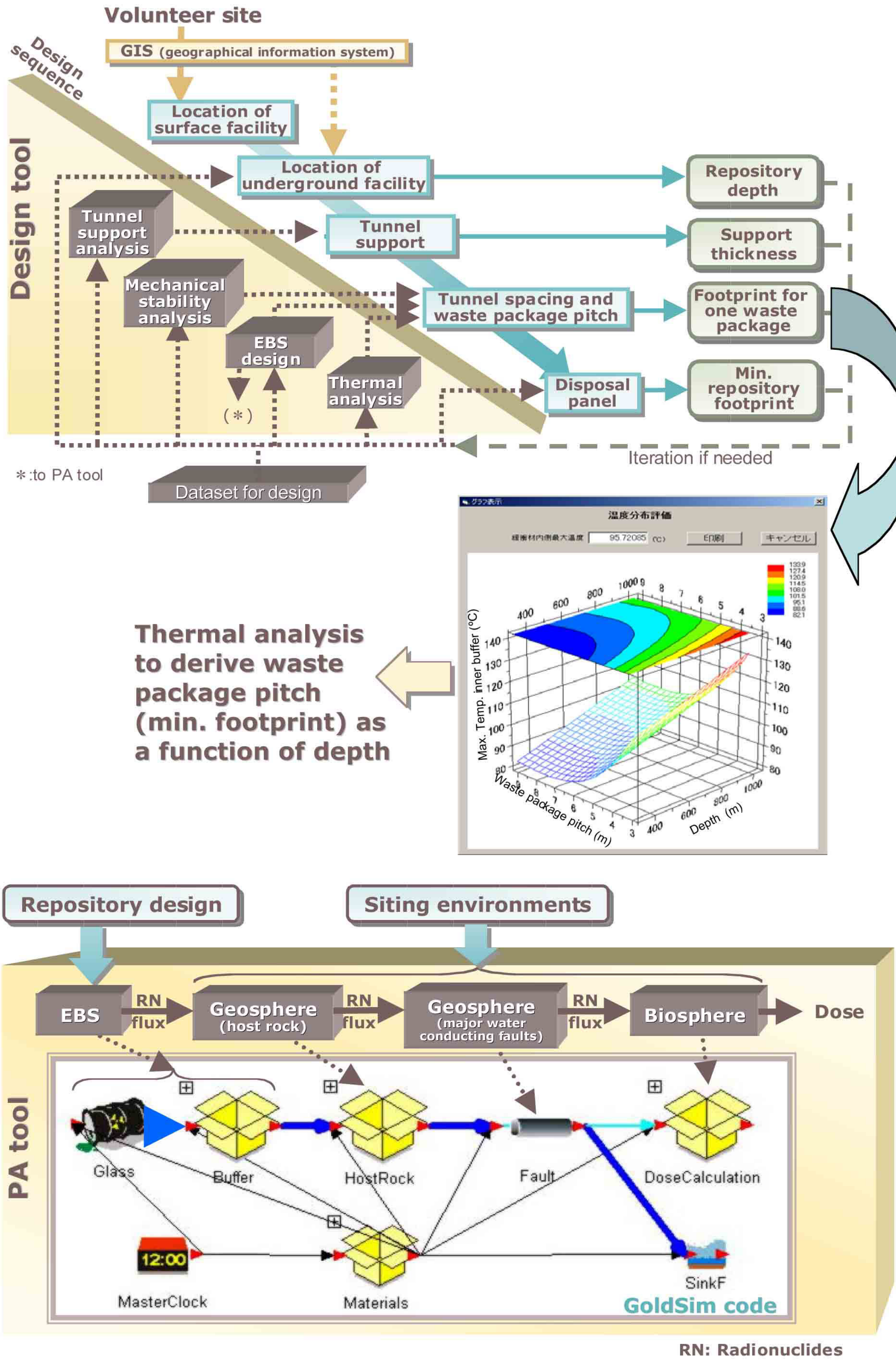

Figure 5-3: Development of scoping assessments of repository design options in potential siting environments.

There are also a number of common activities, including waste packaging, transportation, emplacement and monitoring. At the present stage of repository concept development, the focus for NUMO R&D effort is on the waste emplacement layout, EBS design and the waste emplacement process.

5.3 Focusing R&D for assessing volunteer sites

The general studies become more focused when volunteer sites come forward and literature studies are initiated to assess their suitability. Following a preliminary check on qualification of volunteer sites with respect to volcanoes and active faults, a literature survey will be carried out to assess geological stability on the basis of specified Nationwide Evaluation Factors (NEFs) and Site-Specific Evaluation Factors (SSEFs), which include potential volcanic activity, active faults, rock deformation and seismicity, land uplift/erosion and so on (NUMO, 2004). Relevant information for the qualified sites is also gathered to assess Favourable Factors (FFs), which cover geological, geographical, environmental, and social aspects. After this has been done, it is important to determine whether it would be practical and safe to develop a repository at this site; to do this, a series of appraisal steps have been defined.

As illustrated in Figure 5-4, there is a logical structuring of the output of the literature survey to narrow down the type of RDOs which can come into consideration. The availability of sufficient disposal space is a particular concern that arises from the small size of many Japanese municipalities, the need to keep respect distances from volcanoes and active faults and the complicated geological structures found in many regions of Japan. A first step is thus to determine if it is possible, at least in principle, to fit a repository into any potentially suitable formations available. This is the main emphasis of the top 4 steps in the middle column of Figure 5-4. It is important to provide such a comprehensive and systematic logical structure for development of repository concepts from the outset of the siting process and then to apply it iteratively during later PIA and DIA stages, with appropriate modifications as required.

At this stage, site characteristics may still be rather poorly defined, but, for any site which is not clearly excluded, all available information will be drawn together to outline site-specific repository concepts and analyse these in a quantitative performance assessment. If there are a large number of volunteers, such an assessment can contribute, along with the defined FFs (NUMO, 2004), to ranking of sites for consideration as PIAs.

As preparation for this process, we can identify some information and R&D requirements required to allow this work to proceed and we have already initiated some of this work. Examples of this are:

- Studies of low pH concretes (at JNC and as NUMO / SKB and NUMO / CRIEPI collaborations) to determine the extent to which potential problems caused by use of concrete in low strength or wet host rocks can be minimised (input for steps 4 and 5 in Figure 5-4);
- A review of the thermal stability of bentonite under wet and dry conditions (collaboration with Nagra) to allow the feasibility of design options based on high density waste package emplacement to be assessed (input for step 4 of Figure 5-4; see also Figure 3-2).

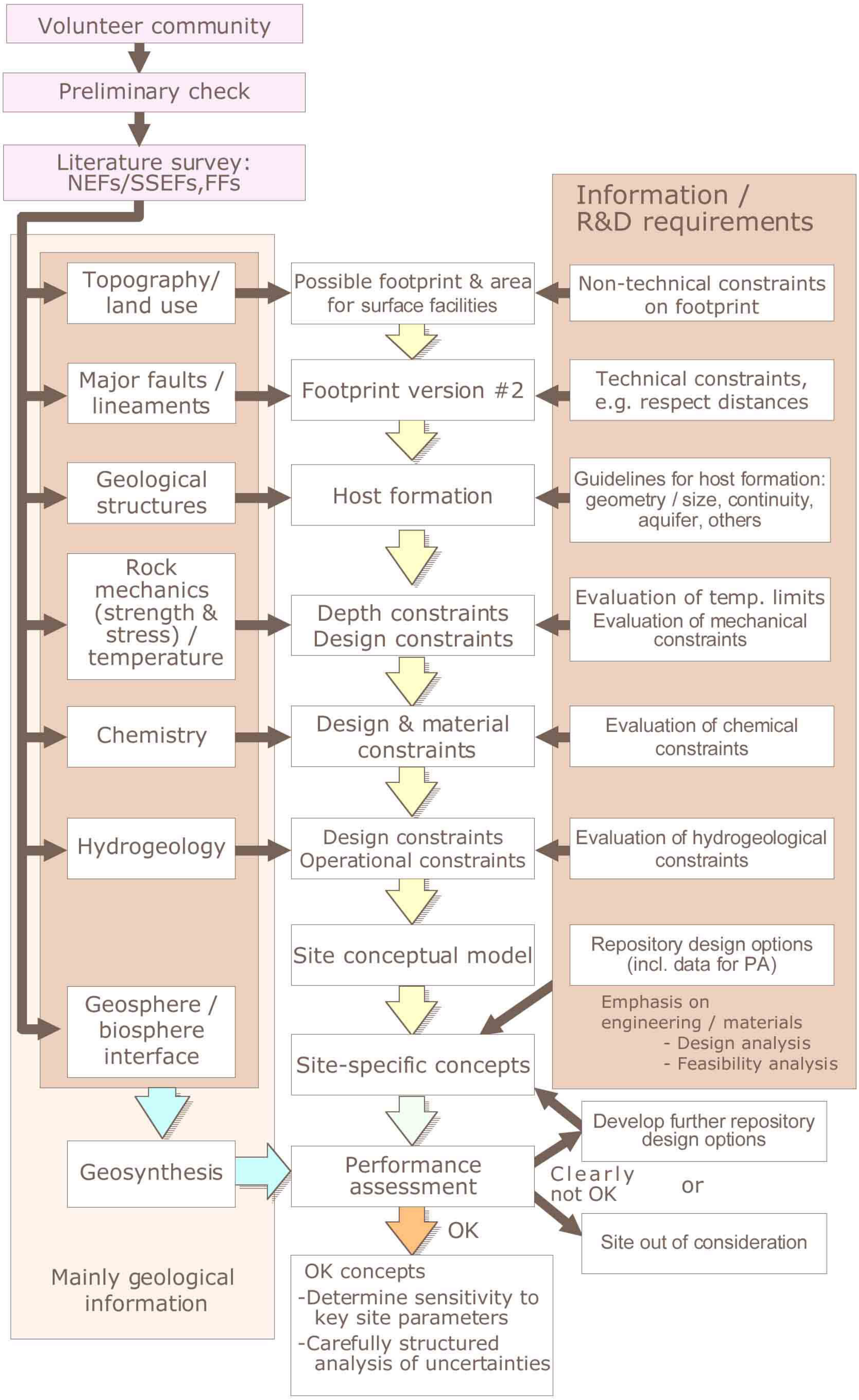

Figure 5-4: **Identification of R&D requirements for volunteer sites during the stage of literature studies.**

5.4 Long-term R&D programme priorities

In addition to the R&D identified above, which has priority due to the implementation time plan (Figure 1-3), there are other R&D projects which need to be initiated soon (or are already ongoing). These projects include studies of the following kinds:

- Important issues specific to Japanese boundary conditions and NUMO repository concepts which are not studied elsewhere (e.g. studies of the long-term tectonic evolution in Japan and its impact on a deep geological repository);
- Areas of common interest which can be efficiently developed in collaboration with an international partner (e.g. NUMO / Posiva co-sponsored workshop on bentonite-cement interaction (NUMO and Posiva, 2004));
- Areas where NUMO wants to establish a leading position; in order to build up credibility with international partners and / or the academic community and to participate in suitable sharing of R&D results (e.g. development of fundamental mechanistic models of compacted bentonite);
- Topics which involve top-level co-ordination / synthesis where NUMO wants to build up in-house expertise to assist in overall programme management (e.g. development of a performance assessment toolbox to allow site-specific comparison of the performance (operational and long-term) of different RDOs);
- Projects which inherently require long-time studies to validate performance assessment models (e.g. long-term corrosion / gas production tests to support future licensing). Many of these fall under "Demonstration and Validation" as defined in Box 5);
- Issues which are common to all disposal concepts (e.g. studies of bentonite);
- Following the progress of ongoing work in Japan and elsewhere, and trying to promote co-ordination of efforts that can provide clear, long-term benefits (e.g. measurement of fundamental chemical-thermodynamic data).

As noted in Section 1.1, there are several organisations in Japan involved in carrying out R&D aimed directly at supporting the NUMO HLW disposal programme. In addition, there are independent programmes for disposal of other wastes (both radioactive and stable) which may have certain common features (e.g. environmental impact analysis aspects). These exist within the framework of a very much larger R&D environment – which produces fundamental information, tools and methodology which may be applicable for NUMO's purposes.

NUMO will play an active co-ordination role, setting goals and milestones and helping to steer and integrate individual R&D projects in the HLW disposal field. We will also encourage sharing of information and co-operation in areas of mutual interest. Information exchange is facilitated by the existing "nuclear infrastructure" in Japan (e.g. JAIF[7], AESJ, conferences and communication initiatives), which will be complemented by focused events (e.g. topical workshops, joint projects) as and when required.

The general R&D community is accessed by NUMO primarily via personal networks and industry / academic communication initiatives. This is complemented, in particular, by NUMO's Domestic Technical Advisory Committee (DTAC), which comprises a group of

[7] JAIF: Japan Atomic Industry Forum, Inc. (http://www.jaif.or.jp/english/index.html).

experts in relevant technical areas. This group is a very valuable interface to the general scientific and engineering community.

At a strategic level, we ensure that we take full advantage of international experience through the active support of our ITAC whose members have experience in almost all major nuclear waste management programmes (records of ITAC meetings are available on our website).

NUMO has already established bilateral links with some of the most advanced national waste management programmes (ANDRA, Nagra, Posiva, SKB, U.S. DOE and UK-Nirex) and has several active collaboration projects ongoing with these partners. In addition, NUMO is a member of EDRAM (International Association for Environmentally Safe Disposal of Radioactive Materials), which includes major nuclear waste management programmes and initiates joint projects in areas of common interest (for details on membership and activities see http://www.edram.org). Further, NUMO is represented in some of the important co-ordination groups of international organisations (e.g. IAEA, OCED/NEA) and supports / participates in international collaboration projects such as the ITC (International School of Underground Waste Storage and Disposal – http://www.itc-school.org).

This wide range of international contacts ensures that NUMO benefits from collaboration and sharing of information and hence avoids unnecessarily duplicating work carried out elsewhere. We recognise, however, that in order to be an "active partner" internationally, we need to have areas of expertise where we are at the forefront, in order to ensure that information exchange is a two-way flow. NUMO's structured process of repository concept development and some of the tools / databases we are developing to support this work have already been a focus of interest from our partners and this seems to be one area in which we can contribute to the research efforts of the international community. We participate in many major international conferences and workshops and are planning to take a more active role in hosting such events in the future.

An example of how R&D projects fulfilling these varied general requirements can be bought together in an integrated manner is illustrated in Figure 5-5, which shows how different Japanese investigations on compacted bentonite are linked together.

We now plan to bring all the considerations above together in a documented R&D programme which will provide a focus for Japanese efforts in the HLW disposal field. This will be a living document, in that it will incorporate the flexibility to respond to the changes in technical and socio-economic boundary conditions to be expected as our staged implementation programme progresses.

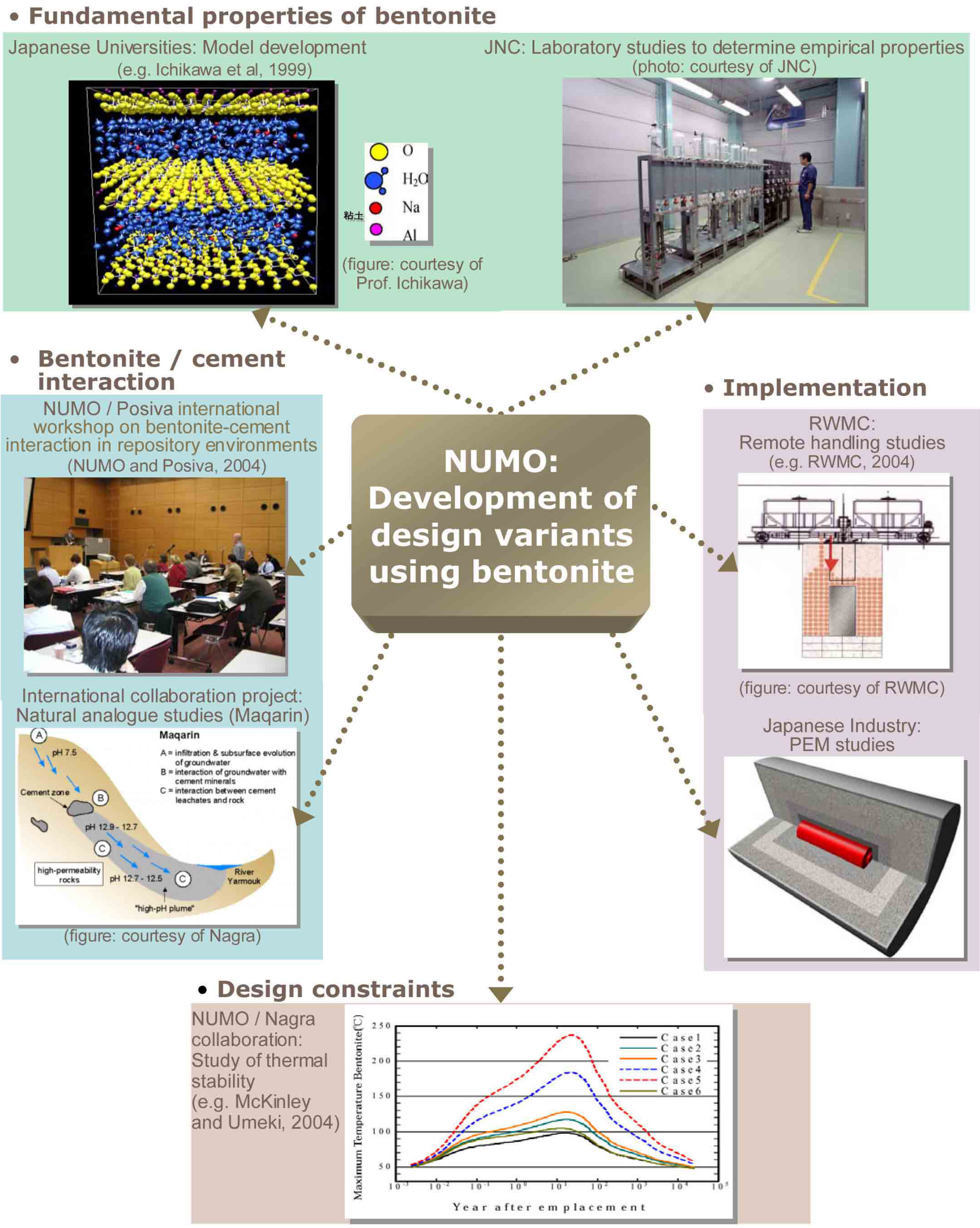

Figure 5-5: **The bentonite R&D programme with an illustration of some key projects in the area of determining fundamental properties of bentonite, bentonite / cement interaction, practical emplacement of bentonite and design constraints set by the requirement to ensure bentonite longevity.**

6 THE FUTURE REPOSITORY CONCEPT PROGRAMME

NUMO's volunteering approach to site selection presents particular challenges for the repository concept development programme. As outlined in the previous chapters, our adoption of this approach explains why we have deliberately chosen to maintain as wide a spectrum of repository design options as possible. This not only allows us flexibility to respond to the diversity of issues to be addressed in the different siting environments resulting from the volunteering process, but also enables us to respond to the desires of interested parties (in particular the local communities).

Following the process shown in Figure 1-6, Chapters 3 and 4 have outlined our progress in developing methodology for selecting suitable repository concepts for potential siting environments, assessing the safety and practicality of site-specific concepts and ranking different sites and RDOs.

As indicated in Figure 1-6, these basic procedures will be iterated further at the stages of literature survey of volunteers, characterisation of PIAs on the basis of surface-based studies and then detailed characterisation of one or more concepts, for one or more DIAs. The programme for site characterisation will also have to be tailored to environments encountered at particular volunteer sites. Although site characterisation plans are still under development, a modular approach similar to that for the repository components is presently under consideration. In this, a catalogue of site characterisation technologies will be prepared which can be assembled to provide a characterisation plan tailored to a specific site.

As emphasised previously, the site characterisation work provides input to, and receives feedback from, the repository concept analyses. The engineering design, performance assessment and site characterisation teams have already worked together – in particular in the tailoring studies described in Sections 3.3 and 3.4. Such projects are considered essential in preparation for the next stages when work on volunteer sites commences. There are obviously uncertainties concerning the characteristics of volunteer sites and their number is also open. In principle, therefore, the initial stages of characterisation of sites may have to run in parallel for several different locations – which could be very diverse in terms of geology, geography and socio-economic setting.

Parallel site characterisation work may strain available resources of expert manpower, specialist equipment and analytical facilities. This will require efficient co-ordination of these programmes in order to follow the tight planned schedule (Figure 1-3). In addition, such co-ordination may also be needed to ensure that equal treatment of volunteers can be clearly shown to the public.

A concern throughout is to ensure that all critical issues can be communicated to interested stakeholders so that key groups – including regulators, independent experts and local communities – fully understand the resultant repository programme and, indeed, are integrated as far as possible into its important decision processes. We thus plan to continue publishing updates on technical developments in this report series, with English language reports on topics which may also be of interest to international audiences.

7 ACKNOWLEDGEMENTS

The work reported in this document was carried out as a collaboration between NUMO and a range of partner organisations and contractors. In particular, some of the concepts and principles were developed together with our International and Domestic Technical Advisory Committees (ITAC / DTAC).

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APPENDIX 1 REPOSITORY COMPONENT CATALOGUE

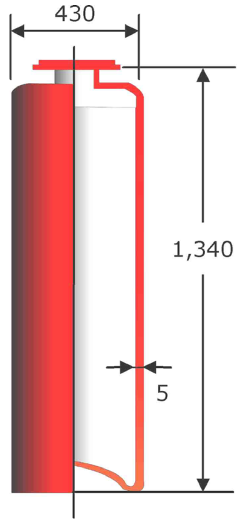
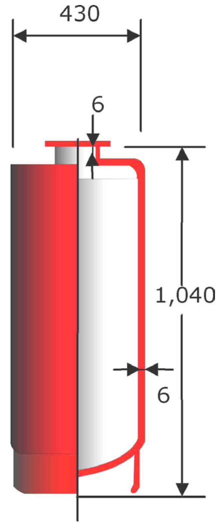
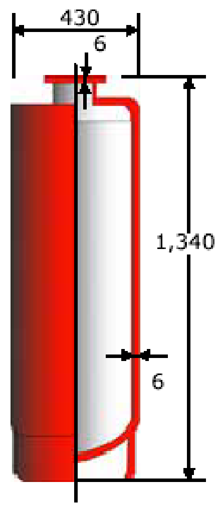
A1-1 Introductory notes

The following points should be noted when considering this catalogue of repository components and geometric options:

- The presentation is illustrative only and the examples of options are chosen to show the range available, rather than attempting to comprehensively cover all possibilities. The only “fixed points” are the specifications of the waste shown in Section A1-2 below.
- Variants of the repository concepts described in the H12 report (e.g. options denoted as “H12” in the catalogue) remain the highest priority for NUMO; other options are being studied in order to maintain flexibility to respond to the siting environments that may be encountered at potential volunteer sites and to the wishes of key stakeholders.
- Comparison of options must be carried out very carefully, as the extent of past experience and the degree of current understanding may vary considerably between particular examples (see discussion in Chapters 2 and 3).

A1-2 HLW designs

The glass provides a low solubility matrix in which the radionuclides are homogeneously distributed. The stainless steel canister ensures containment up to the point of encapsulation in the overpack.

	BNFL / COGEMA	JNC	JNFL
Dimensions (unit: mm)			
Weight (kg)	~500	~400	~500

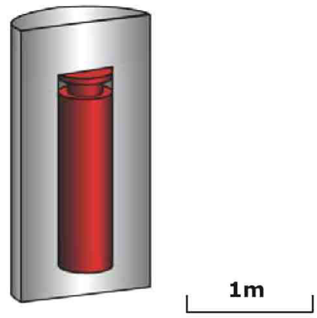
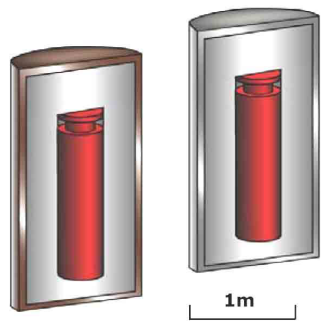
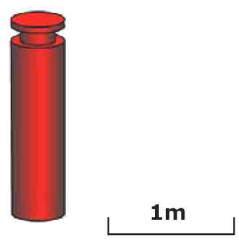
(RWMC, 1998)

The specifications for the borosilicate glass matrix and the stainless steel fabrication canister are given by the reprocessing organisation. Note that, for operational reasons, the canister is not completely filled with glass and a certain void space remains.

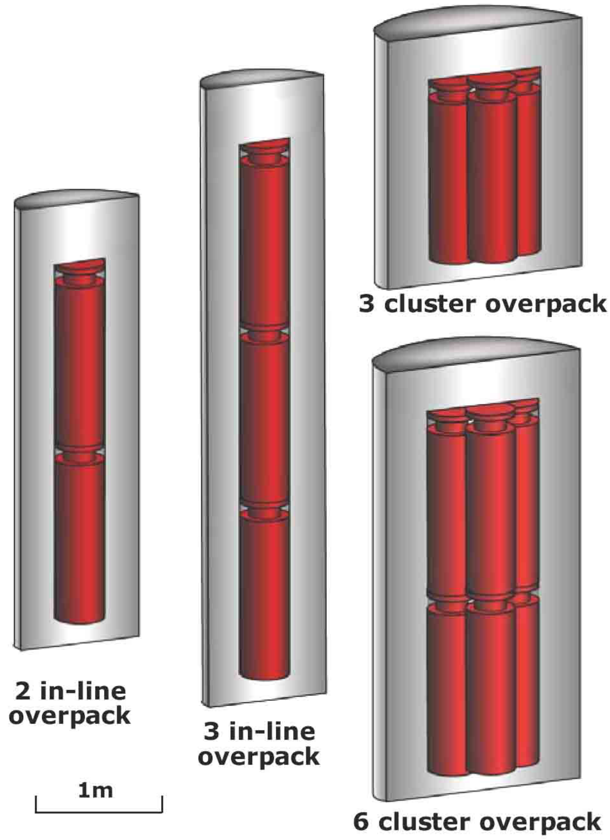
A1-3 Safety-critical engineered barrier components

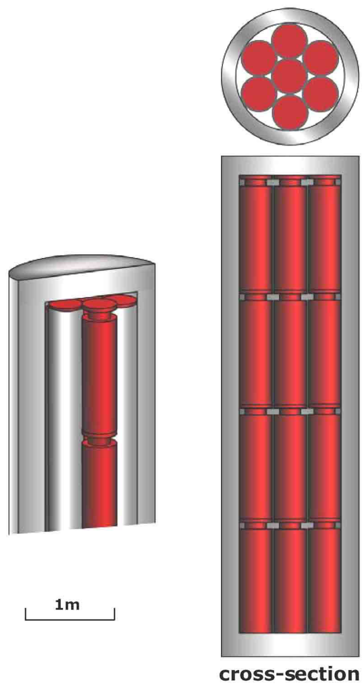
A1-3.1 Overpack

The overpack has mechanical and radiation protection roles during handling and emplacement. After emplacement, it may provide a period of complete containment during the radiogenic thermal transient, when conditions are rather dynamic and may be strongly coupled (e.g. thermal and water saturation profiles in the buffer); although this may not be critical for safety, it can contribute to simplifying the presentation of the safety case. After loss of integrity, a corroded steel overpack may also serve important roles as a redox buffer (consuming radiolytic oxidants to ensure local conditions remain reducing), a physical barrier to solute transport (if failure is localised) and a chemical barrier (sorbing radionuclides or including them irreversibly into secondary minerals formed as corrosion products).

1. Thick steel overpack (H12 reference)	
Corrosion allowance option: • Contains a single waste container; • Sufficiently thick to be mechanically stable, reduce external dose rate and to allow for corrosion over a 1,000 year containment lifetime.	
2. Composite overpack	
Corrosion resistance option: • Thin layer provides corrosion resistance and steel inner vessel provides mechnical strength; • Cu and Ti corrosion barriers considered as H12 variants; other materials also possible (e.g. strong ceramics).	
3. No overpack	
Option proposed for some concepts involving high performance geological barriers (e.g. ANDRA, 2001).	

<table>
<tr><td colspan="2">4. Multiple waste canister overpack</td></tr>
<tr><td>2-6 waste canister overpack:

Essentially a conventional overpack but with more than one waste canister;
Simple steel overpack is shown but composite overpacks are also feasible and could reduce weight/size of the overpack;
Void space in the cluster designs filled with glass beads.
</td><td>
</td></tr>
<tr><td colspan="2">5. Multi-purpose, very large overpack ("cask")</td></tr>
<tr><td>Containing up to 28 waste canisters:

Could be designed for multiple use - transport / storage / disposal (with additional external packaging, neutron shield, etc. as required);
Internal void space filled with glass beads.
</td><td>
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</table>

A1-3.2 Buffer

The buffer plays many important roles in the H12 "robust EBS" design (see Figure 2.3). These include:

- Mechanical protection from small rock movements due to its plasticity;
- Hydraulic barrier, its extremely low hydraulic conductivity ensuring that solute transport occurs predominantly by diffusion;
- Colloid filtration / microbe barrier due to its microporous structure;
- Chemical buffer, buffering pH into the mildly alkaline range (enhances the longevity of overpack and glass matrix) and providing additional redox buffer capacity (e.g. from included pyrite);
- Radionuclide sorption: delaying and spreading releases of many key radionuclides.

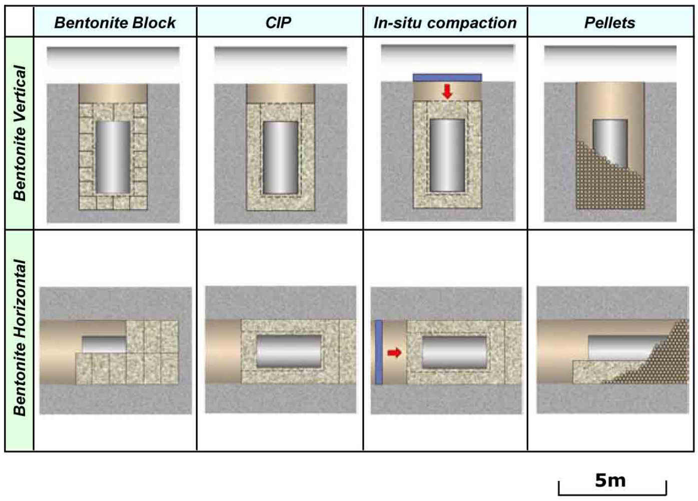
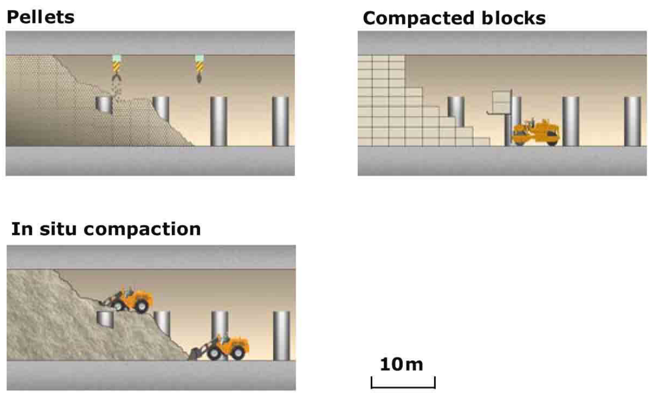
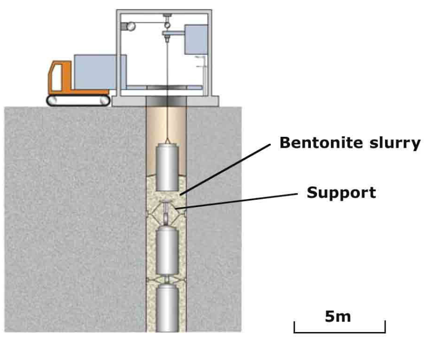
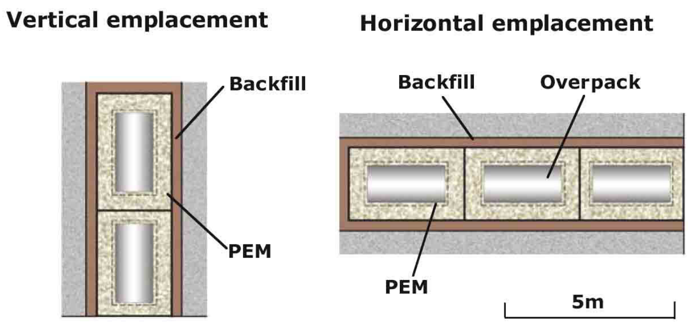
In addition, the following functions are expected.

- Thermal conduction: limiting maximum temperatures within the EBS;
- Thermal stability: key properties of bentonite are preserved to above 100°C in the wet state and significantly higher temperatures if it is kept dry.

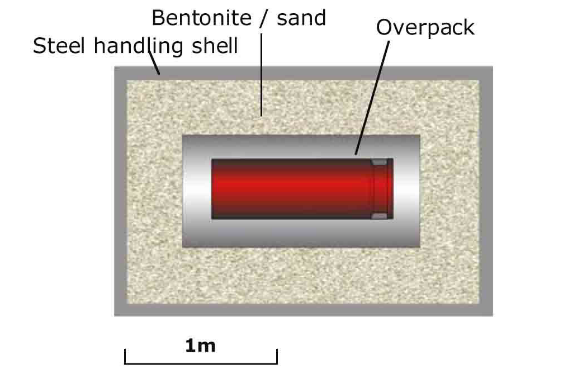
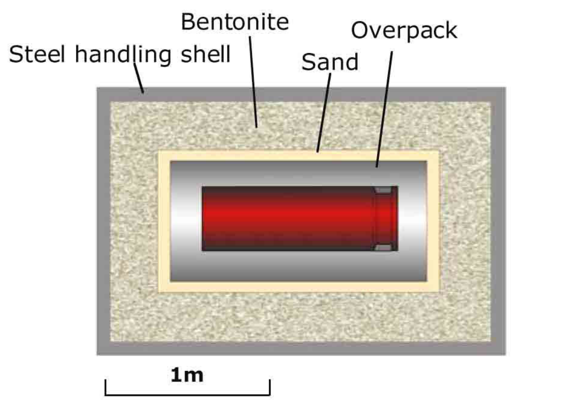
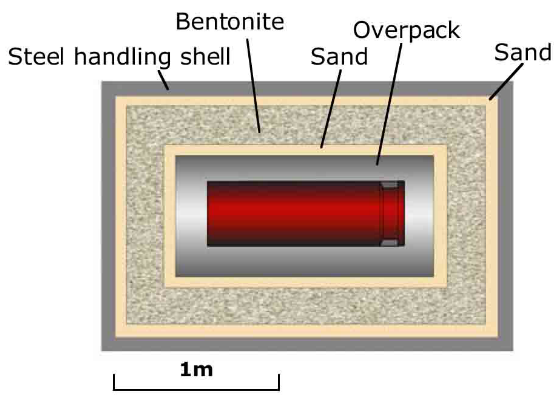
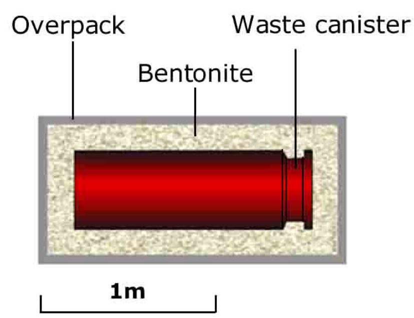
A1-3.2.1 Buffer materials

- Bentonite-based material. Major component usually Na-montmorillonite with different amounts of minor and trace minerals such as quartz, calcite, feldspar, pyrite, etc. Exact composition depends on the bentonite source and pretreatment. H12 reference is a Japanese commercial product Kunigel V1.
- Bentonite / sand mixtures. Significant quantities of quartz sand can be added to increase thermal conductivity of the buffer and decrease risk of canister sinking without detriment to other favourable bentonite properties (e.g. plasticity, low permeability, sorption, colloid filtration). A 70:30 mixture is specified as a reference in the H12 concept.
- The bentonite composition and the type and quantity of additives (e.g. sand, metal, zeolite) can be varied to tailor properties to particular site conditions (e.g. groundwater salinity).
- Alternative buffer materials have been proposed (e.g. other clays, zeolite). However, the buffer plays a key role in the H12 safety case and a large body of data for bentonite exists in Japan and abroad; hence such alternatives are not being considered by NUMO at present.

A1-3.2.2 Buffer emplacement options

1. H12: in-situ buffer emplacement for overpacks in small tunnels or pits • Compacted blocks. • Cold Isostatically Pressed (CIP) units. • Pellets. • In-situ compaction. • Combinations.	
2. In-situ emplacement for large volume (e.g. caverns for very large casks) • Pellets. • In-situ compaction. • Compacted blocks. • Combination.	
3. In-situ 'wet' emplacement for boreholes (bentonite slurry) • Displaced bentonite mud is pumped to adjacent unfilled borehole to avoid overflows.	
4. Prefabricated buffer • Waste, overpack and buffer contained within a handling shell (prefabricated EBS module (PEM); see A1-3.2.3) for ease of emplacement.	

A1-3.2.3 Prefabricated EBS module (PEM) designs

1. H12-based design • Waste canister. • Overpack. • Bentonite / sand buffer. • Steel handling shell.	
2. Variant 1 with separated bentonite and sand • 100% bentonite buffer. • Addition of a sand layer around the overpack: - acts to remove the possibility of overpack sinking by creep; - increases radionuclide transport resistance during the period of H_2 gas generation. (McKinley et al., 2004a)	
3. Variant 2 with separated bentonite and sand • 100% bentonite buffer. • Addition of a second sand layer outside the bentonite (acts to reduce the possibility of bentonite erosion by flowing groundwater). (Toyota and McKinley, 1998)	
4. Variant with external shell serving as overpack • Waste canister. • Bentonite buffer. • Outer steel layer (acts as overpack and handling shell for the unit). • Equivalent to the Integrated Waste Package (IWP) proposed by Apted (1998).	

A1-4 Additional engineered barriers with operational / post-closure safety roles

A1-4.1 Backfill

Apart from the volume immediately around the overpack, many repository designs include void spaces in critical areas. The material used to fill such zones is termed “backfill”. Apart from physically reducing the instability of openings, such backfill may have additional hydraulic, chemical or radionuclide retention barrier roles.

Various backfill compositions have been considered:

- Bentonite / aggregate (sand / gravel) – mixtures containing 10-30% bentonite were studied in the H12 project;
- Crushed rock / bentonite – potentially uses rock spoil from the excavations and use of the host rock avoids introducing additional components into the system. Performance depends very much on the rock involved;
- Crushed rock – use of the host rock avoids introducing additional components into the system and reduces volume of rock spoil. Performance depends very much on the rock involved;
- Concrete-based grout – in areas where potential high pH alteration will not be detrimental (e.g. physically or hydrologically isolated from the waste emplacement areas), cement-based grout or concrete could be considered as a backfill material;
- Bentonite or rock with other additives such as zeolites could improve specific properties (such as sorption of specific radionuclides) if this is required;
- Sacrificial backfill to act as a chemical buffer between concrete tunnel liner and bentonite buffer material (McKinley et al., 2004b).

Selection of a backfill composition and an appropriate emplacement technique will depend very much on details of the siting environment and the required safety roles of backfill in a specific repository concept.

A1-4.2 Liners

Depending on the properties of the host rock and underground openings, liners may be needed for various reasons, e.g.:

- Ensuring the mechanical stability of openings;
- Reducing water inflow;
- Providing a smooth, regular surface to aid buffer / backfill emplacement (and QA);
- Providing a support structure for transportation (road, rail) or services (ventilation, power, drainage).

A1-4.2.1 Liner material options

Shotcrete / rock bolt combinations □ Standard engineering option. □ Often used as temporary measure before more substantial liners are emplaced.	□ Water ingress reduction. □ Some rock mechanical support e.g. where fracturing locally reduces rock competence.
Concrete (standard OPC-based) □ Standard engineering option. □ Long experience with use. □ Economical option. □ Can be problematic in conjunction with bentonite (high pH causes alteration).	□ Rock mechnical support where host rock is too weak to allow self-supporting openings or where stability cannot be ensured over sufficiently long periods. □ Water ingress prevention.
Low pH concrete □ Modification to a standard engineering option. □ Little practical experience with use of this new material. □ Maybe acceptable in conjunction with bentonite (no high pH alteration).	□ Rock mechnical support where host rock is too weak to allow self-supporting openings or where stability cannot be ensured over sufficiently long periods. □ Water ingress prevention.
Steel □ Standard engineering option. □ Long experience with use. □ May allow for removal before emplacement of waste packages or backfilling of tunnels. □ Gas generation (corrosion) could be a problem in tight formations.	□ Rock mechnical support where host rock is too weak to allow self-supporting openings or where stability cannot be ensured over sufficiently long periods. □ Water ingress reduction / prevention.
Plastic / resin □ Non-standard option. □ Limited experience with large scale use. □ May be undesirable if left in place (organic materials) after emplacement but may allow relatively easy removal.	□ Water ingress reduction.
Geotextiles □ Used in combination with other materials such as concrete.	□ Drainage behind concrete liners.
Novel materials □ Ceramics. (No or very little experience)	□ Water reduction. □ Mechnical support.

A1-4.2.2 Examples of liner applications

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1. Pits

- Low pH concrete.
- Steel.
- Plastic.
- Ceramic.

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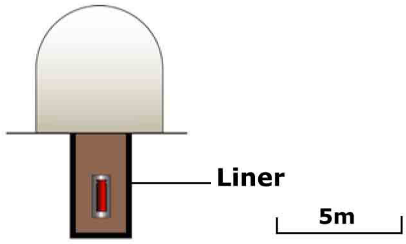

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2. Horizontal emplacement tunnels

In-situ emplacement and PEM:

- Low pH concrete;
- Steel;
- Plastic.

PEM only:

- Shotcrete + rock bolts;
- OPC concrete.

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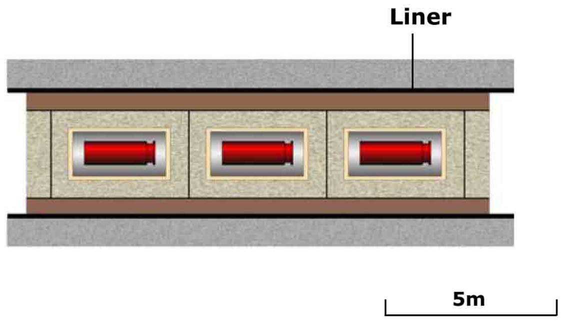

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3. Disposal tunnels (vertical emplacement)

- Low pH concrete.
- OPC concrete.
- Steel (removable).
- Shotcrete + rock bolts (only in good rock).

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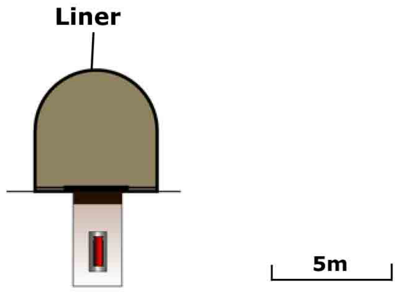

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4. Access tunnels

- Low pH concrete.
- OPC concrete.
- Steel.
- Shotcrete + rock bolts probably not sufficient (operational safety).

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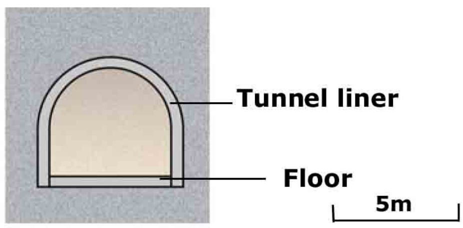

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5. Caverns / working areas

- Low pH concrete.
- OPC concrete.
- Steel.
- Shotcrete + rock bolts probably not considered sufficient (operational safety).
- Use of geotextiles for drainage behind other liner material, e.g. concrete.

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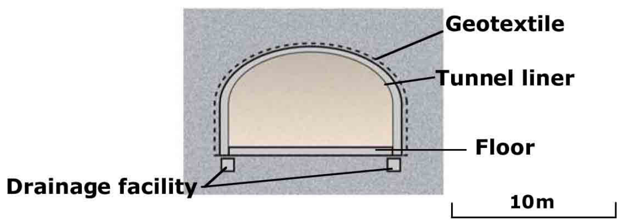

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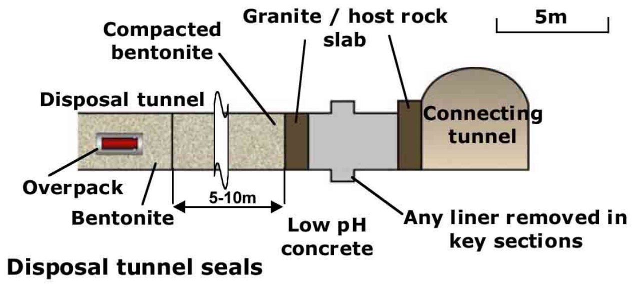
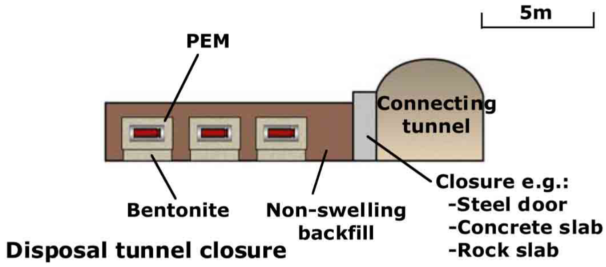
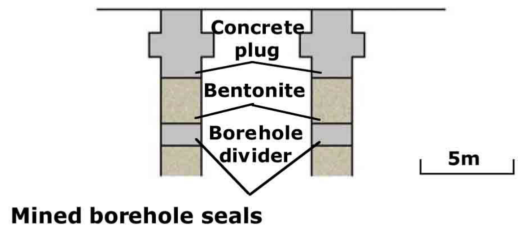
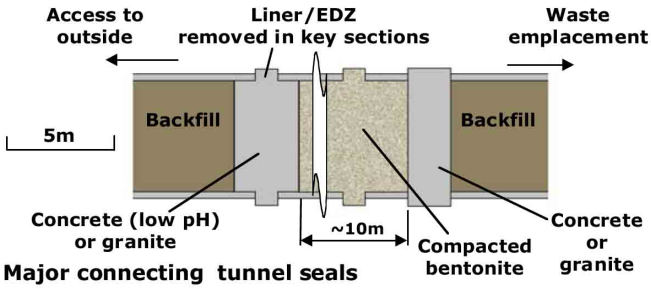
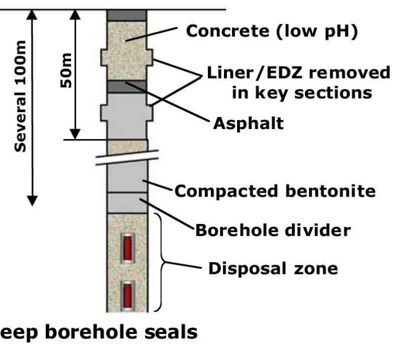
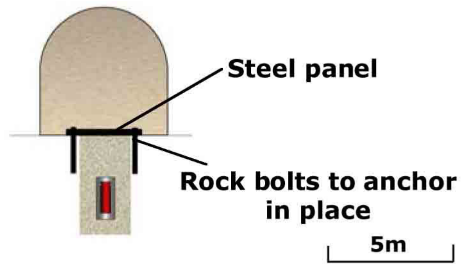
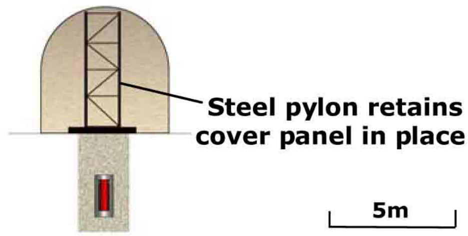
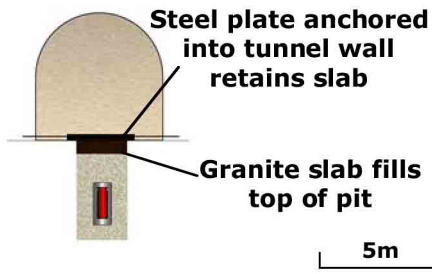
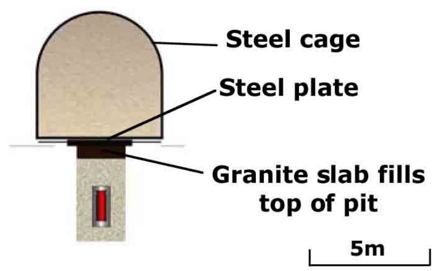
A1-4.3 Seals

Plugs and seals to physically close tunnels and holes may be required at various locations within a repository. A wide range of designs have been examined, depending on the host rock properties and the requirements for the seal in terms of operational and post-closure performance.

1. Disposal tunnel seal (H12) □ In situ emplacement of EBS. □ Retains swelling buffer material. □ Access tunnels may remain open.	
2. Disposal tunnel closure (alternative) □ For PEM. □ For ease of operation to ensure non-swelling backfill does not spill into access tunnels.	
3. Mined borehole seal **Example includes:** □ Physical seal by metal packer ("borehole divider"); □ "Sacrificial" bentonite barrier; □ Upper concrete plug (ideally low-pH composition).	
4. Major connecting tunnel seals □ Isolate disposal areas. □ Prevent / minimise groundwater transport along access tunnel EDZ from disposal areas.	
5. Vertical deep borehole seals □ Major safety feature of the concept to ensure isolation of wastes from surface environment.	

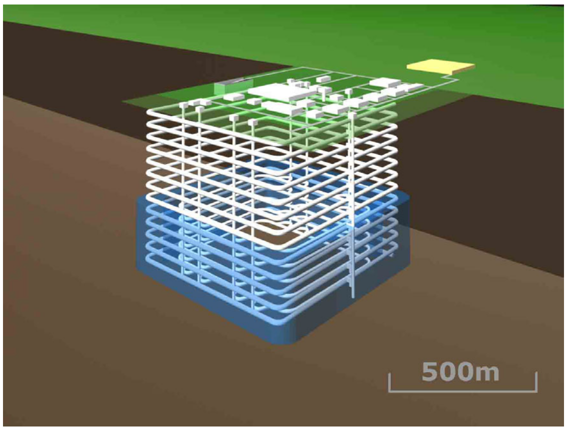
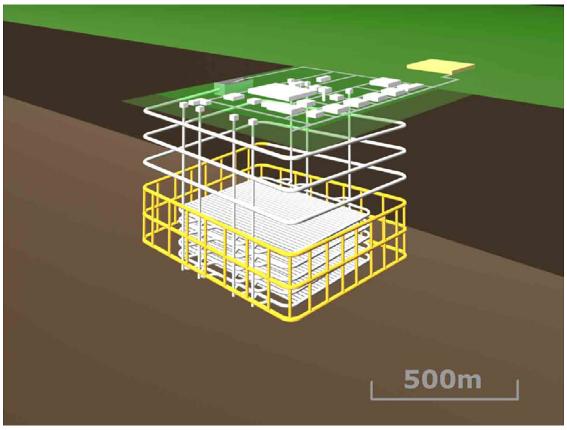
A1-4.4 Disposal pit cap

In cases where bentonite is emplaced into holes under wet conditions, a cap may be needed to prevent extrusion into the overlying tunnel and subsequent loss of density. Such a cap might have to resist rather high swelling pressures. Practicality of various options depends on the properties of the host rock and operational constraints (e.g. whether or not capping is done as a remotely operated procedure).

1. Rock bolted steel panel (H12 option)	
2. Steel support (H12 option)	
3. Granite slab – type I	
4. Granite slab – type II	

A1-4.5 External engineered barrier

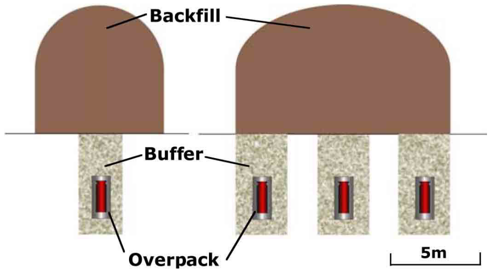
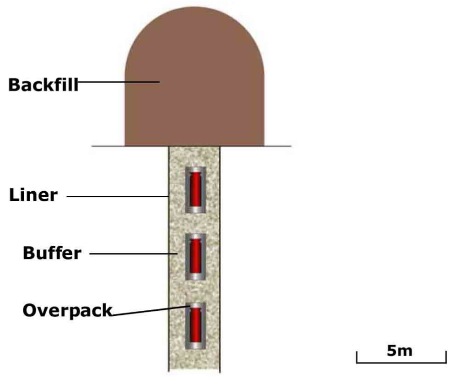
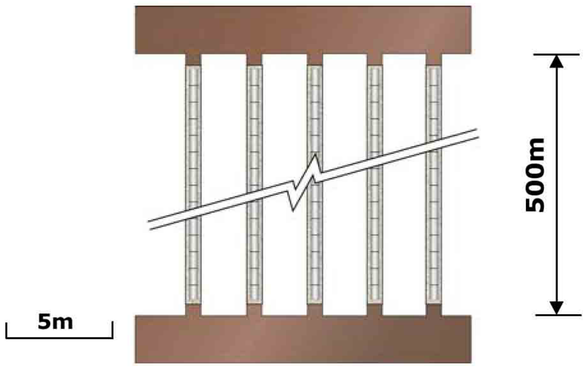
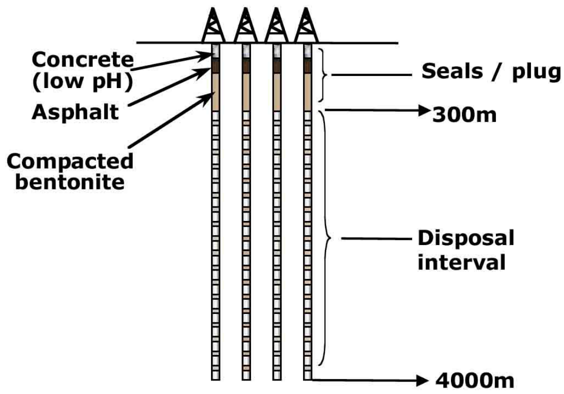
For the sake of completeness, options of surrounding the repository with an engineered barrier are illustrated. Although such designs have not been studied in any detail, the principles involved have been examined elsewhere, most notably the SKB "WP cave" concept (SKB, 1986).

1. Low-permeability barrier - Surrounding low-permeability barriers have been included in concepts for near-surface repositories for low-level radioactive and chemotoxic wastes. - Example considers grout injection from boreholes drilled from a spiral access ramp to construct such a barrier.	
2. Hydraulic cage - High-permeability barrier reduces gradients over (and hence water flow through) the repository. - Example considers sand-filled boreholes, hydrofracturing etc. from a spiral access ramp to create the high conductivity region.	

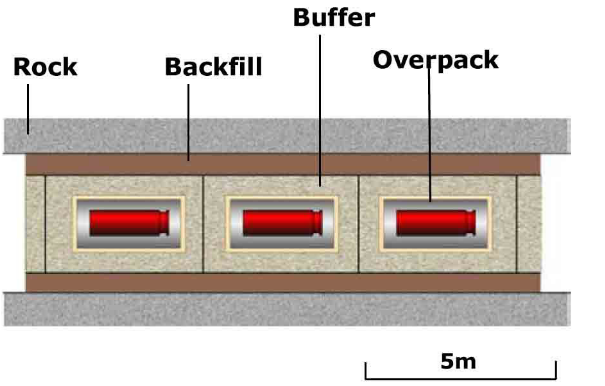
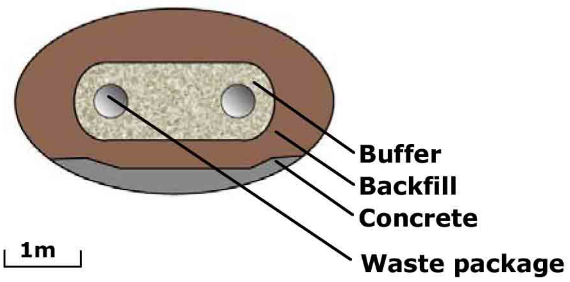
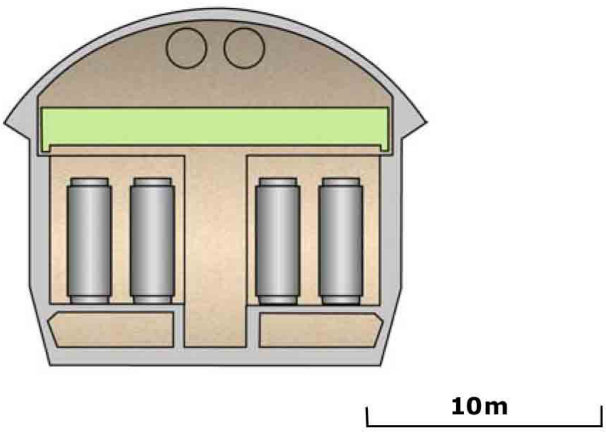
A1-5 Emplacement geometry

Depending on the properties of the siting environment and constraints set by rock mechanics and thermal loading, a range of different emplacement geometries can be considered.

A1-5.1 Vertical

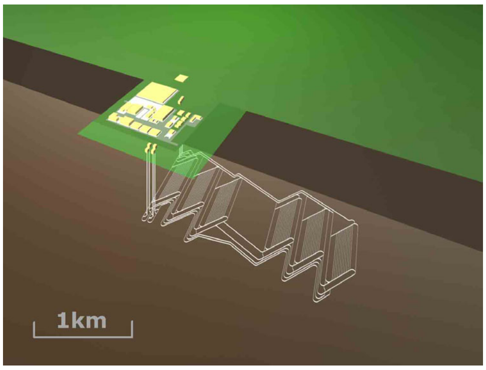
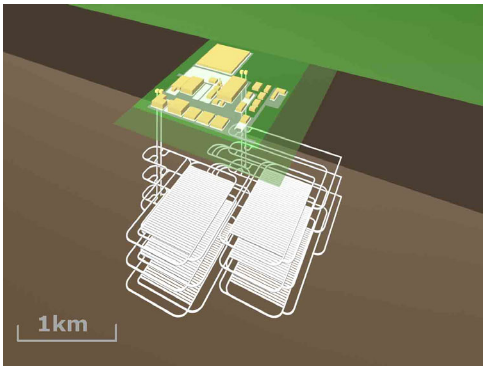
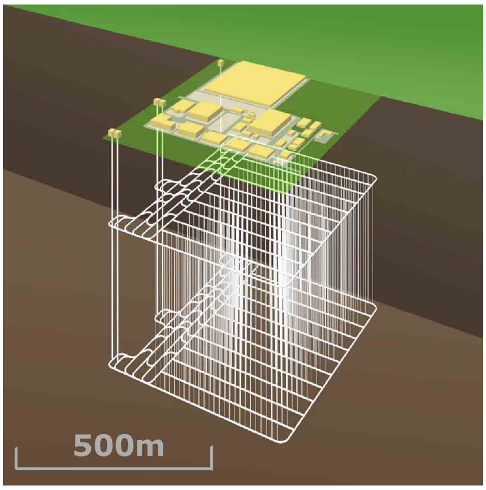
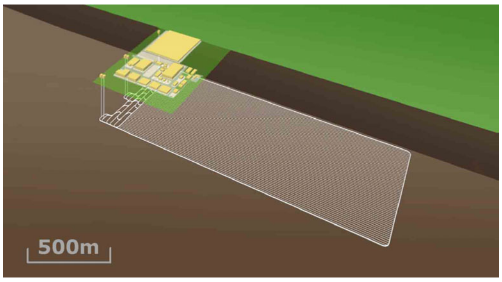
1. Pits □ Single waste package is emplaced in each pit. □ Buffer may be emplaced in-situ or as PEM.	 (left: H12)
2. Short boreholes (multiplex disposal) □ Multiple waste packages are emplaced in short boreholes. □ EBS may be emplaced in-situ or as PEM.	
3. Mined boreholes □ Boreholes some 100s of metres in depth. □ Waste packages most likely emplaced as PEM.	
4. Deep boreholes □ Boreholes some 1000s of metres in depth to ensure isolation. □ Waste packages most likely to be PEM. □ Safety ensured by isolation rather than specific host rock.	

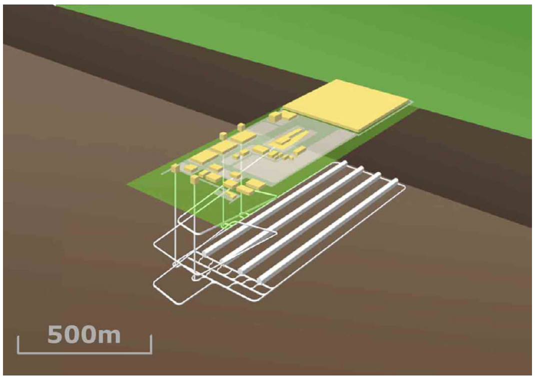
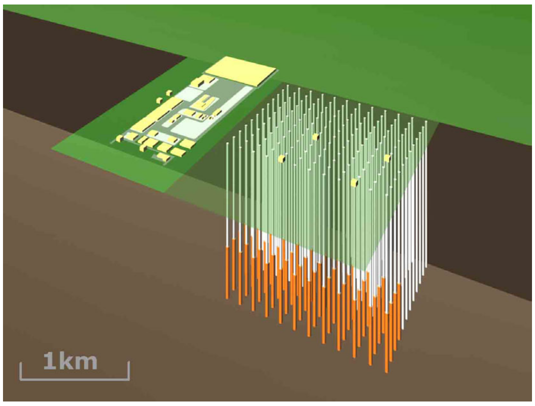
A1-5.2 Horizontal

1. In-tunnel – linear (H12) • Waste packages emplaced centrally in the disposal tunnel. • Buffer may be emplaced in-situ or as PEM. • PEM may be placed end-to-end or with backfill / buffer filling spaces between. • For in-situ emplacement, waste packages are separated by sections of buffer.	
2. In-tunnel – duplex • Two waste packages emplaced side-by-side (but separated by buffer). • Has been developed for cases where anisotropic rock stresses do not allow the construction of circular tunnels.	
3. Caverns • Waste packages arranged in large open cavern. • May have an extended period between waste emplacement and emplacement of buffer / backfill.	

A1-6 Underground layout

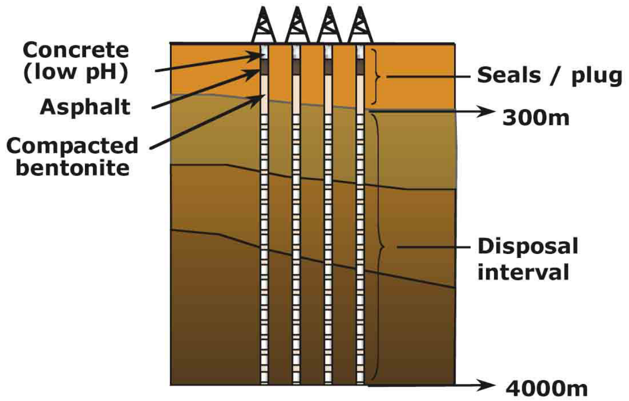
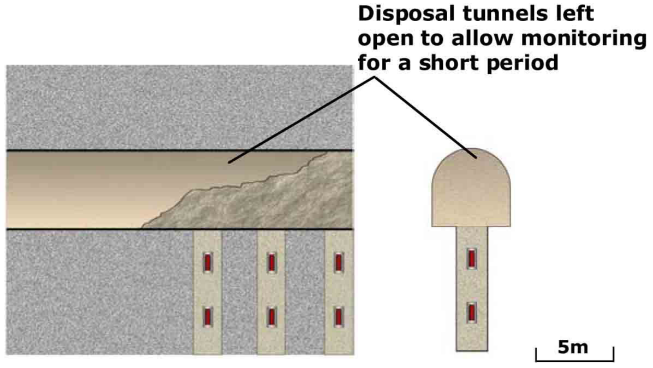
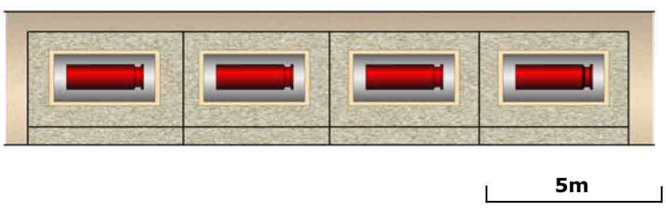
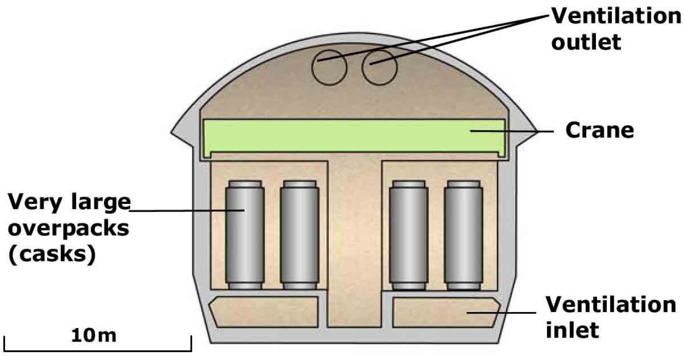
The layout will be strongly constrained by the properties and geometry of the host rock.

1. Single level – distributed emplacement panels (H12) □ Waste emplaced in pits or tunnels, spread over several panels (tailored to site geology).	
2. Multiple level □ Waste emplaced in pits or tunnels, spread over several panels (tailored to site geology). □ Panels stacked on several levels to make optimum use of thick host rock.	
3. Vertical mined boreholes □ Extension of the multi-level layout to further increase utilisation of a thick formation with good isolation properties.	
4. Long horizontal tunnels □ Example could be used to take advantage of coastal sites (emplacement zone extending off-shore). □ Could be appropriate to a thin host rock formation. □ Probably utilise PEM.	

5. Caverns □ Mainly considered for use with very large overpacks. □ Dense waste disposal is possible if caverns are left without buffer / backfill for the thermal period. □ Large stable openings allow long period of institutional control and monitoring (and retrievability) due to delay in backfilling.	
6. Vertical deep boreholes □ Great depth of disposal increases waste isolation. □ Requirements on host formation reduced. □ Minimal EBS may be sufficient (e.g. overpack only or simple IWP). N.B.: This option involves some fundamental changes in the basic safety philosophy, but is included for the sake of completeness.	

A1-7 Disposal procedures

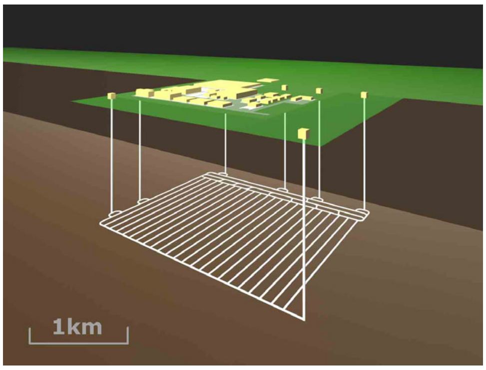
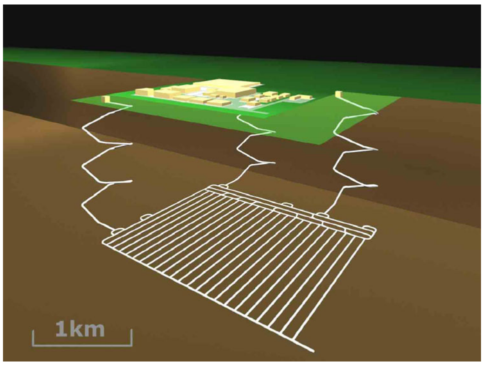
The processes involved in waste disposal may vary, in particular depending on the extent to which there is a desire or requirement for monitoring / inspectability and ease (or difficulty) of retrieval. Some extreme variants are illustrated.

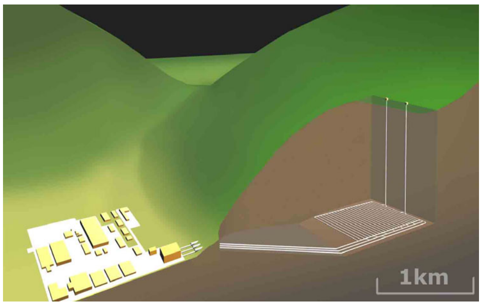
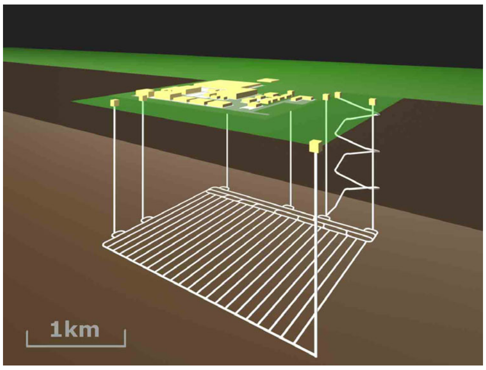
1. No monitoring / not inspectable **Retrieval made difficult:** □ Immediate backfilling & sealing of disposal tunnels/boreholes; □ Example for vertical deep boreholes.	
2. Immediate emplacement of buffer but access allows monitoring e.g. : □ Vertical mined boreholes; □ Short boreholes; □ Pits with disposal tunnels left open.	
3. Delayed backfilling around wastes to allow monitoring and ease of retrieval e.g.: □ PEMs in long horizontal tunnels.	
4. Long-term monitoring with inspectability and ease of retrieval □ Caverns. N.B.: Ventilation, drainage and inspection facilities would be needed during an extended open period to maintain the waste packages in good condition before backfilling.	

A1-8 Surface facilities and underground access

A1-8.1 Access routes from surface

Idealised examples are shown for illustration. For final design, the repository layout and EBS chosen, the properties of the host rock and overlying formations and the geography / topography of the site will all have to be taken into account.

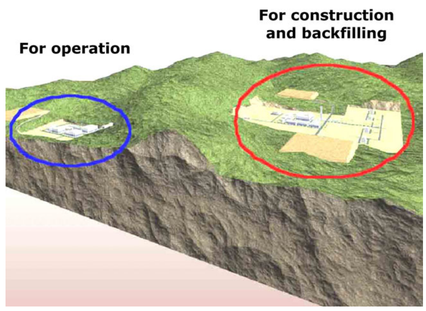
<table>
<tr><td>1. Vertical shafts</td><td>
</td></tr>
<tr><td>2. Inclined tunnels (ramps)
(shafts are ventilation shafts)</td><td>


</td></tr>
<tr><td>3. Combination of shafts and ramp
□ Likely combination for many design options if waste transport in a ramp is preferred.
□ Shaft access allows more rapid transport of personnel and other EBS / construction materials.</td><td>
</td></tr>
</table>

A1-8.2 Surface facilities

There is great flexibility in the design and layout of surface facilities. Two extreme cases are illustrated – an extended design with all facilities for reception, inspection and encapsulation of the waste and for construction and operation of the repository (including storage of rock spoil) on the surface at a single location. The second shows an example for the case where useable land area at the repository site is limited and hence facilities are either constructed underground (e.g. waste reception, encapsulation) or at other locations (e.g. rock spoil storage).

<table>
<tr>
<td>1. Extended surface area
□ No limitations on surface use.
□ Most likely at sites with flat topography and large available land areas.</td>
<td>
</td>
</tr>
<tr>
<td>2. Limited surface area
□ Makes maximum use of underground structures.
□ Probably appropriate to hilly and / or coastal sites.</td>
<td>




</td>
</tr>
</table>

APPENDIX 2 THE IMPORTANCE OF POST-CLOSURE SAFETY ASSESSMENT IN REPOSITORY CONCEPT DEVELOPMENT

A2-1 Decision making in stepwise development of the repository

An ultimate goal of geological disposal is to isolate radioactive waste safely from humans and the environment over timescales far beyond the normal horizon of social and technical planning. The development of a deep geological repository takes place in several stages within a stepwise process of planning and implementation. This process requires periods on the timescale of decades to reach the stage where repository operations can begin. At the end of each stage, a decision is made whether to move forward and whether the requirements for the next stage need to be adjusted.

Significant decision points early in the disposal programme may include the choice of host rock and repository concept for the particular Preliminary Investigation Areas (PIAs) selected for further investigation. Once a site is selected and an initial repository concept defined, the decisions involve planning the scope of investigation from the surface and underground, including demonstrations of the engineering feasibility of key repository elements, choices between design variants and the optimisation of underground layout. At later stages, the programme will focus on the licensing procedures for construction, operation and closure.

Throughout repository development, the importance to decision-making of convincing arguments for long-term safety is high. For many decisions, a safety case is one of the key sources of information on which the decision is based. Generic understanding of relevant phenomena, as well as site- and concept-specific models and data, are initially limited, with many unresolved issues. Site characterisation, repository design and safety assessment are therefore activities that run throughout the stepwise repository development processes or are repeated iteratively, with the safety case being developed incrementally.

A siting and design strategy is adopted that aims to develop a predictable and robust system. Robust systems are characterised by simple, well understood or easily characterised features and phenomena and an absence of, or insensitivity to, uncertain or detrimental phenomena. An assessment strategy is adopted that provides a range of arguments and analyses for the safety case that are well founded are supported, where possible, by multiple lines of evidence, and are adequate in their treatment of uncertainty. The safety case may, however, emphasise a limited number of processes or features of the repository and its environment, if these are particularly well understood and insensitive to perturbations.

Thus, site selection, development of a suitable design for a selected site, site characterisation and other R&D activities are carried out in an iterative, stepwise manner, providing a framework for:

- Comprehensive scientific and technical investigations and analyses by the implementer, including safety assessment and an evaluation of uncertainty, in the course of each stage of repository development;
- Thorough scientific and technical review and staged development of guidance and requirements by the regulators;

- Political and social involvement of interested stakeholders, to take into account their needs.

A2-2 Definitions and general features

There are numerous special terms that are used in discussions on the safety of waste repositories. Box 3 gives definitions of the more common ones, using text from international consensus documents where possible. Active discussion currently concerns the definition of the safety case and how it should be used. Although broad agreement exists on the general intention, there is no real unanimity between countries and organisations on precise requirements, definition or application. Despite having an origin and use in normal industrial practice, the term does not exist in formal radioactive waste regulations in most countries and is difficult to translate into many languages - including Japanese. At its simplest level, it is a collection of data, analyses and arguments used to show how a repository system performs and provides safety. This collection includes evidence of the intrinsic quality of the site and design, rigorous modelling aimed at producing quantitative dose or risk estimates to demonstrate regulatory compliance (i.e. safety assessment) and also “softer” information to illustrate how the system or its components work. Examples of such information are simplified descriptions of key processes, observations of natural analogues, comparison with natural geochemical fluxes, etc.

Safety assessment is a formal method for quantifying the behaviour of each component of the disposal system as it evolves with time and of translating this behaviour into estimates of its impact on the overall performance of the repository. It attempts to assess the quantitative impacts of the following factors that characterise the disposal system (also taking into account their variability):

- The properties of the radioactive waste to be disposed of;
- The materials and structures planned to be used and the processes by which these interact;
- The characteristics of the geological environment surrounding the repository and the processes taking place in it;
- The behaviour of radionuclides in the near field, geosphere and biosphere, and their radiological impact on human health.

Although there are differences between national programmes in the detailed procedures that are followed in the course of a safety assessment, the broad tasks that are carried out in the course of any post-closure safety assessment are essentially the same. The major elements are:

- System understanding: carefully describe the appearance or state of the repository when it has just been closed, and consider what changes the repository could undergo in time as a consequence of both internal processes within the repository and external forces;
- Scenario analysis: identify broad scenarios that illustrate the range of possibilities for the evolution of the repository and its surrounding environment;
- Consequence analysis: analyse these scenarios and evaluate their consequences for safety, taking into account all relevant uncertainties.

The essence of safety assessment is the use of models of the time-dependent behaviour of the components of the system, or of processes occurring within them. These produce quantitative description of future states of the system and resulting radionuclide behaviour. These models should be tested as thoroughly as possible.

As a consequence of the need to project the behaviour of the disposal system into the distant future and to large spatial scales, safety assessment models rely heavily on information which is extrapolated in both time and space. Part of this extrapolation includes deciding how best to represent the geometry of the repository and the host rock in the models. As a result of spatial and temporal variability, in both the processes modelled and the properties which they affect, there is considerable uncertainty associated with safety assessment results. This uncertainty increases with increasing time, particularly beyond the timescale over which geological stability can be confidently assured (100ka – 1Ma).

In safety assessments it is not assumed that our knowledge of the natural system or of the behaviour of the engineered barriers is perfect or complete. However, the safety case should not rely on properties of the geological environment or on the performance of the engineered barriers for which knowledge is poor or lacking. In safety assessment, uncertainty about the future evolution of the system can generally be taken into consideration by:

- Selecting appropriate scenarios;
- Making conservative assumptions (overestimating consequences);
- Studying the influence on safety assessment results of the assumptions used, by sensitivity analyses and also by “what if? ” analyses;
- Defining stylised situations in the case of the biosphere and future human actions.

A key issue is showing how much uncertainty exists in each argument and what its impact is on confidence in overall safety. Perhaps the key definition is that a safety case comprises multiple lines of arguments to show safety (including indicating the level of confidence in the models and data used for its evaluation), with an emphasis on frequent iterations of safety assessment as knowledge grows. This is the approach being adopted by NUMO which sees it as part of a staged process that will need dialogue throughout, with both the public and regulators and also peer review by a wide range of technical expert groups.

A2-3 Making a safety case in the context of the Japanese programme

The concept of geological disposal in Japan is similar to that in other countries, being based on a multi-barrier system which combines the natural geological environment with engineered barriers. Particular consideration is given to the long-term stability of the geological environment, taking into account the fact that Japan is located in a tectonically active zone. Due to Japan’s complex geology, an engineered barrier system (EBS) with sufficient margins in its isolation functions to accommodate a wide range of geological environments and their potential future states was developed in H12 (see Section 2.3). The major contribution to overall safety barrier performance of the disposal system is provided by the near field, while the remainder of the geosphere serves to reinforce and complement the performance of the EBS (see Section 2.3).

The safety concept assumes that major disruptive events can be excluded by site selection. Geological environments having favourable characteristics for the disposal system provide the basis for repository design. If the safety functions of the geological disposal system can be assured, minor amounts of radioactivity released from the EBS will further decay and concentrations will be reduced by dilution during the long migration period in the geosphere.

Thus, the basic functions of the repository system provide intrinsic, long-term, passive safety. To support this safety concept, R&D activities have focused on understanding natural system attributes that favour EBS performance, including relative tectonic stability, low groundwater flux, favourable geochemistry and a low risk of disruptive events. Safety assessment has been conducted for a defined repository system, taking alternative future evolutions of the system into account in order to illustrate the robustness of its intrinsic safety features (JNC, 2000).

A2-3.1 Confidence in the intrinsic safety features of the disposal concept

In order to promote confidence in the technical feasibility of the disposal concept, it is required to:

- Select geological environments which are stable for a long time and provide favourable conditions for EBS performance and significant radionuclide retardation capacity;
- Develop an appropriate design for containment and retardation of radionuclides in the EBS for the selected geological environments.

Selection of geological environments suitable for a repository
Important natural phenomena which could influence the long-term stability of the geological environment include fault activity, volcanic activity, uplift and erosion, and climatic and sea-level changes. The occurrence of these natural phenomena and the extent of changes in the geological environment caused by them were investigated over various timescales extending out to over a hundred thousand years, based on field studies in regions where the long-term impact of these phenomena could be observed. These studies showed that the location of sudden localised phenomena, such as volcanic activity and major fault movement, can be well specified and their effects can thus be avoided by selecting an appropriate disposal site. On the other hand, gradual phenomena such as uplift and denudation or climatic and sea-level changes are more ubiquitous. It is, nevertheless, possible to estimate future trends and potential effects by extrapolating data obtained from the field studies. The conclusion from the studies is that it is possible to select a sufficiently stable environment for geological disposal. Nationwide Evaluation Factors and Site-Specific Evaluation Factors for qualification of sites have been developed by NUMO for selection of the PIAs (NUMO, 2004).

The characteristics of the geological environment which are important in terms of design and safety of the repository include size and geometric configuration of host rock, groundwater flow rates, rock permeability, the geochemical characteristics of groundwater, the thermal and mechanical properties of rock formations and solute transport properties. Favourable Factors including these characteristics are being defined to help determine the overall practicality of a repository project (NUMO, 2004).

The datasets relevant to these characteristics will be used for subsequent studies to determine appropriate repository designs and characteristics of the engineered barriers. The geological data also provide essential input to the safety assessment, for evaluating potential doses resulting from expected evolution scenarios.

Demonstration of repository design and engineering technology

The design requirements for the EBS and the general disposal facility were initially specified based on utilisation of currently available technology, taking aspects such as economics and environmental impact into consideration. The practical feasibility of designing and emplacing the EBS and constructing the disposal facility is then examined for a given siting environment. The design of the EBS and disposal facility should be sufficiently flexible at early stages of repository development to ensure that it can be finally tailored to the specific characteristics of a potential disposal site and respond to developments in science and technology in the decades until it is finally implemented.

This combination of engineering design studies, taking into account the information for a given siting environment, should show that the intrinsic safety features of the repository will perform as expected, and are practicable from both engineering and economic viewpoints. In addition, demonstrating that emplacement is feasible requires building confidence that the repository can be safely constructed and that the resulting construction will be of very high quality (i.e. largely free of defects in workmanship that would affect its barrier functions).

A2-3.2 Safety assessment to illustrate robustness of the barrier functions

While the main safety functions of the repository are intrinsic to the design and location within a deep geological system, understanding the level of robustness of the proposed system in various geological conditions or under changes in system conditions can only be evaluated through long-term repository performance assessment. The assessment method developed and applied should be able to evaluate the safety functions and the level of robustness of the proposed system under various conditions.

Scenario development

In order to reduce the risk of overlooking potentially important scenarios, a systematic scenario analysis methodology has been developed and applied in H12. A comprehensive list of FEPs (Features, Events and Processes) is firstly developed by collating the FEP lists developed in other projects (e.g. OECD/NEA, 1997; Nagra, 1994). The only scenarios modelled in detail in H12 are "groundwater scenarios" (scenarios in which moving groundwater provides the pathways for transfer of radionuclides from the repository to the surface environment). As shown in Figure A2-1, these include:

- A Base Scenario, in which external events and processes such as natural geological and climatic phenomena, initial EBS defects and future human activities are excluded;
- A set of perturbation scenarios, in which the potential impacts of external events and processes are examined.

A Reference Case is defined for the Base Scenario, incorporating a particular set of geological characteristics, design features, model assumptions and parameter values. Alternative cases are also defined for the Base Scenario (with alternative geological settings, design features, model assumptions or parameter values) and for perturbation scenarios.

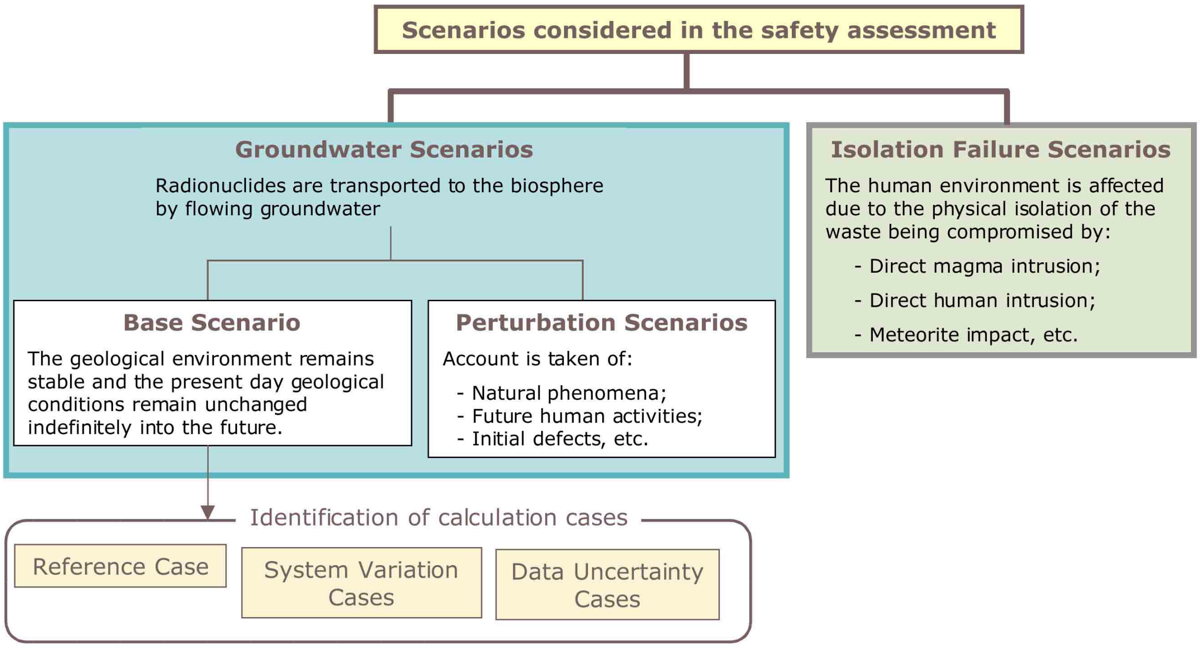


Figure A2-1: Classification of scenarios in H12.

Some FEPs could generate complete "isolation failure scenarios" (scenarios in which the human environment is directly affected due to the loss of physical isolation of the waste). Examples are direct human intrusion and extreme scenarios associated with natural phenomena that bring the wastes directly to the surface. These FEPs were screened out (e.g. on the basis that they could be excluded by siting). Nevertheless, some "what if?" analyses have been carried out to illustrate the magnitude of potential consequences, and thus the importance of siting the repository in a suitable environment.

Development of models and databases

Based on a list of feasible scenarios, models which simulate relevant phenomena in detail, together with associated databases, were established in order to quantify selected scenarios. Models were developed to simulate the evolution of the EBS and subsequent radionuclide migration in the rock surrounding the buffer material.

If dose or risk is to be used as an indicator of whether or not releases to the biosphere are acceptable from the point of view of safety, some assumptions regarding the evolution of the biosphere, including the habits of potentially exposed groups, must inevitably be made. An approach adopted in H12 to this problem is to employ a stylised representation of conditions in the biosphere, including the habits of potentially exposed groups, using the concept of Reference Biospheres.

In H12, it was assumed that radionuclides are transported through the host rock to a major water-conducting fault (retardation taken into account) which leads to a shallow aquifer (no retardation considered) near the ground surface. Radionuclides then enter the biosphere system via a geosphere-biosphere interface (GBI). A number of GBI types (e.g. river, deep well, marine) are possible, since a wide range of geological environments throughout Japan have to be taken into account. Among them, a river in a coastal plain is selected for the Reference Case.

From the standpoint of the performance assessor, data are used not only as input for models, but also to provide support for the choice of scenarios, support for the assumed favourable characteristics of the disposal system as well as for specific model assumptions (or their conservatism), yardsticks for comparison with complementary performance indicators (e.g. natural radiotoxity fluxes), etc. The collection of such data requires coordinated input from a number of specialised disciplines.

The models mentioned above were linked together in a safety assessment model chain, which allows the performance of the entire geological disposal system to be assessed. The Reference Case was analysed using this model chain for a repository containing 40,000 waste packages. The calculated results for the Reference Case indicate that sufficient containment of radionuclides can be achieved by the EBS and the near-field host rock, provided the groundwater flow rate is reasonably low (Figure A2-2)*.

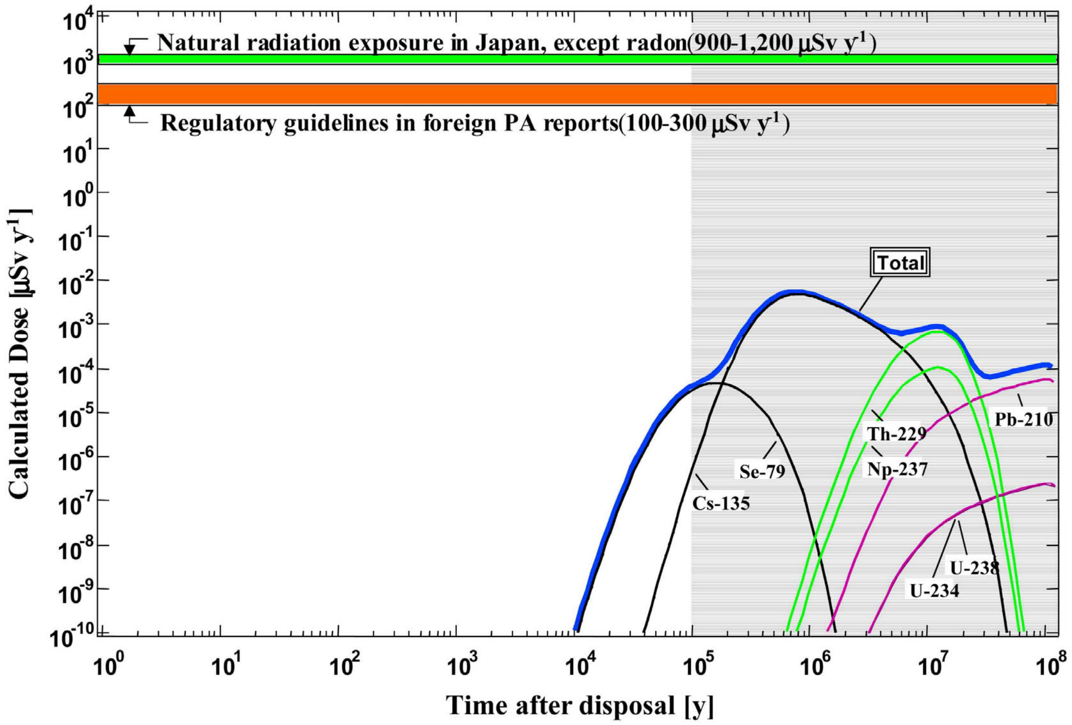
The approach and results of the H12 safety assessment have been compared with those of other national programmes. There are differences in the disposal concepts and assessment methodologies adopted internationally, and an understanding of the background to, and reasons for, these differences can contribute to confidence in the reliability of the H12 safety assessment. The fact that different disposal concepts and assessment approaches indicate the safety of geological disposal also suggests that there is scope for optimisation of disposal concepts and assessment methods in the future to fit site-specific conditions.

As dose estimates inevitably include significant uncertainties from biosphere modelling, supplementary safety indicators have been investigated. For example, it has been shown that comparison of radionuclide concentrations calculated at several positions in a disposal system with concentrations of naturally occurring radionuclides provides a useful perspective on repository safety.

The methodology developed in the H12 project provides a basis for the performance assessment of a geological disposal system at a site to be selected in the future. At the site-specific stage it will be important to incorporate realistic geological features and optimised engineered barriers without compromising the robustness in the methodology that is essential to a defendable assessment.

As discussed in Chapters 4 and 5, goals have been specified for developing a second generation of performance assessment tools, and the R&D required to support and, eventually, validate them has been considered. Indeed this development work has already been initiated to ensure that the capacity to compare the long-term safety of repository concepts specific to defined sites is available for the evaluation of PIAs planned within the next decade.

* N.B.: These calculations are extended to very long times to illustrate trends – showing, for example, that very extensively retarded actinide chains do not give rise to calculated doses above those of the more mobile fission products (Cs + Se). As discussed in the companion report (NUMO, 2004), geological stability can be assumed in a well chosen site for at least 10^5 years; any model output beyond such times must be regarded as extremely uncertain.



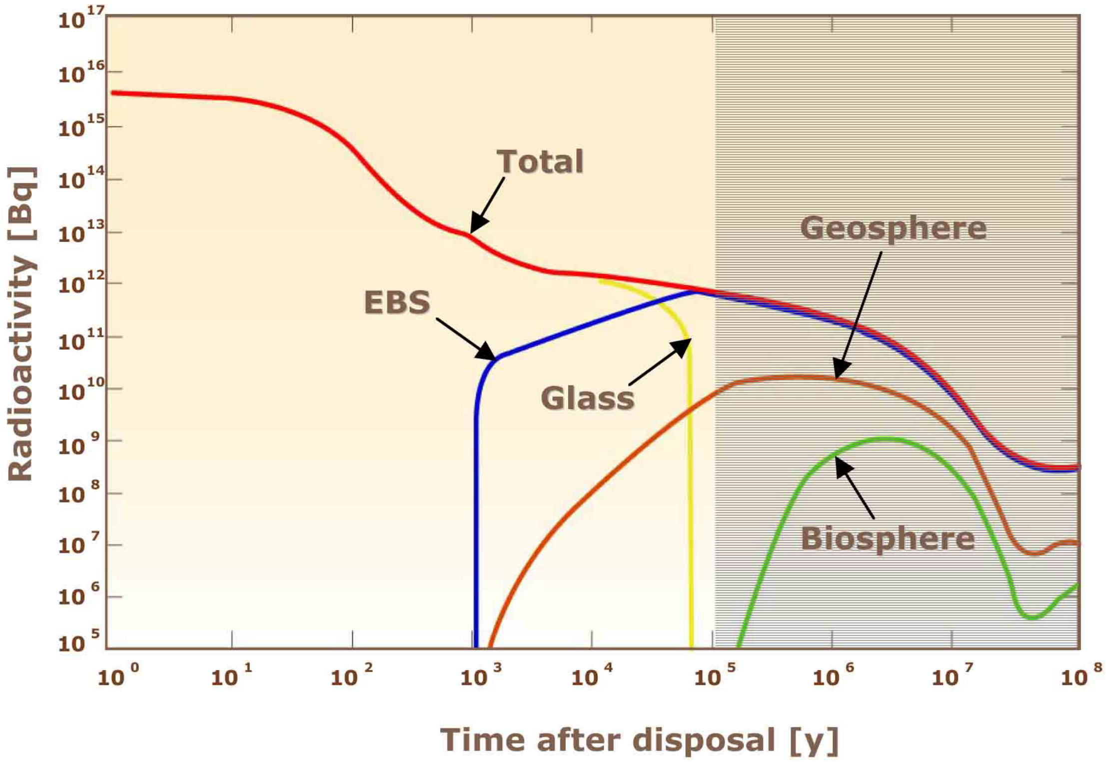


Figure A2-2: **Reference Case dose evaluation and the combined radioactivity per waste package of all radionuclides in different system components as a function of time (after Makino et al., 2002). The repository is assumed to contain 40,000 waste packages and all packages fail 1,000 years after disposal. The shaded area indicates the period of increasing uncertainty in the applicability of all model components.**