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H17: Development and management of the technical knowledge base for the geological disposal of HLW

- Knowledge Management Report -

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Japan Nuclear Cycle Development Institute

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Knowledge Management Report

Executive Summary

The H17 project represents a status overview of R&D carried out under the current JNC programme (2001 - 2005) to support the Japanese HLW project at the transition point between the generic phase, which ended with the H12 project, and the truly site-specific phase which will commence when volunteers come forward allowing NUMO's staged implementation approach to be initiated. Three technical reports document progress made during this period in the areas of geoscience, repository engineering technology and safety assessment methodology, following the format of past progress reports. The present report puts this work in context by outlining a new approach which will be applied to plan, structure and prioritise future R&D.

The Japanese HLW programme and key advances since H12 are summarised in Chapter 1. The second chapter outlines the principles of deep geological disposal, focusing on passive safety established by multiple engineered and natural barriers. Assessing safety after closure depends on utilisation of a modelling approach, which is inherently associated with uncertainties in both the characterisation of the repository system and the evolution of this system over long time periods. A practical way of optimising flexibility to respond to new understanding and also build up public support involves stepwise implementation, associated with a transparent decision-making process and a structured R&D programme. Knowledge management provides a convenient method for structuring existing information and identifying priorities for future R&D when requirements are well defined. As an example, the requirements for establishing the post-closure safety case (based on NEA guidelines) can be used to structure the knowledge base required to support it. In Chapter 3, a template illustrating the structured flow of knowledge to make a safety case at the stage of selecting sites for preliminary characterisation investigations is used to map knowledge requirements against that available, in order to identify future knowledge development needs. This is complemented by analysis of further knowledge needs to support main stakeholders and an outline of the "wish list" for a formal knowledge management system. Finally, Chapter 4 looks to the future and considers how knowledge management may play a central role in the long-term evolution of the Japanese nuclear waste management programme.

Geological disposal of radioactive waste is recognised to be a safe and environmentally sound method to provide a final solution to the management of this material. Due to the very long time over which high-level radioactive waste remains hazardous, however, safety has to be assured by a series of passive engineered and natural barriers which require no active human involvement via monitoring or maintenance to provide safety. In the case of a well selected site, the stable properties of the deep geological environment greatly facilitate the demonstration of safety, assuring the longevity of the engineered barriers and protecting them from the many perturbations which can occur at or near the surface. To provide defence in depth, multiple barriers are selected which provide a very high degree of redundancy, ensuring that performance levels will be sufficient even in the case of failure of one or more

independent barriers. Many different combinations of natural and engineered barriers have been demonstrated to deliver the very high levels of long-term safety required of such projects.

In the discussion of safety, the particular boundary conditions for repositories as compared to conventional engineering projects or nuclear facilities have to be emphasised. In particular, safety assessment over periods of hundreds of thousands of years and the requirement to characterise in detail geological media on the scale of cubic kilometres is unique. It is clearly impossible to demonstrate safety directly and hence a formal approach based on simulation models is required. Rather than attempting to predict the future, a series of representative scenarios can be analysed which will bracket potential evolutions of the system. This includes stylised representations of the biosphere, as the development of human activities is very uncertain over even very short timescales.

Due to great public concern about such projects, ethical aspects of radioactive waste disposal have received extensive consideration. Two particular principles are often emphasised – intra-generational and inter-generational equity. The latter leads to the requirement that the generation which has benefited from nuclear power generation takes full responsibility for its safe disposal. For long-lived waste, the passive system of a closed repository is clearly preferable to any kind of long-term store. Nevertheless, there has recently been increased discussion of the desire to maintain the ability of future generations to contribute to the decision-making process – leading to development of stepwise approaches to project implementation with clear decision points and assured reversibility of decisions should this be required.

An open and transparent decision-making process also contributes towards the intra-generational equity issue of assuring that the localisation of the impact of repository projects as compared to the national benefits of power generation is handled fairly. In the Japanese programme, such consideration has led to the decision to adopt a volunteer approach to initiation of a staged siting process and an open policy of ensuring that host communities receive benefits to compensate them for accepting this role. Active dialogue with stakeholders will identify their concerns and particular programme modifications can be introduced to address these – e.g. demonstration facilities, monitoring systems and institutional control periods prior to final closure. The proposed NUMO staged implementation programme is outlined and the key role of supporting R&D discussed.

The demonstration of safety is critical to development of a repository project and is important at many of the decision points in the phased implementation process. Such a demonstration includes not only numerical modelling but also supporting argumentation and evidence which is termed the “safety case”. This will evolve with time, at early stages being conditional on resolution of inevitable uncertainties at the beginning of a project.

For later licensing steps, the safety case has to be completely convincing to both regulators and other interested stakeholders. Input has to be derived not only from the safety assessment groups, but also from those responsible for site characterisation and facility design. Argumentation must be consistent, but would be presented in different ways to make it comprehensible to all interested audiences.

For repositories, the safety case can be divided into the pre-closure period which, in principle, is similar to other nuclear facilities, comprising a consideration of both conventional and radiological hazards and being supported by monitoring and incident logging procedures. The safety after closure generally concentrates entirely on radiological hazards, even though these might be spread over large areas and occur only in the distant future. Regulatory hazard limits may be specified for workers over the open period and for the general population before and after closure. The demonstration of compliance with the last of these is the most difficult, requiring multiple lines of evidence and demonstrable robustness to balance the uncertainties which are inevitable in such assessments.

Disposal technology is a multi-disciplinary field and needs a wide range of relevant information to develop its safety case. Knowledge is defined here in the very widest sense to include all of the information, both explicit and tacit, which underpins a repository project. It obviously increases with time and is essential to all stakeholders, including the implementer, the regulator, political decision-makers and the general public. Although essential for developing a project, a structured approach to assuring that all relevant knowledge is available becomes particularly critical at times when major project decisions have to be made.

Knowledge management covers all aspects of the development, integration, quality assurance, communication and maintenance / archiving of such knowledge – including data, information, understanding and experience. In order to ensure that required knowledge is accessible to users and that gaps can be identified and prioritised, it is important that knowledge bases are structured in a clear and logical manner. In particular, if the requirements of the user are structured in a formal way – e.g. using a requirements management system – this can, in turn, be used to directly structure the associated knowledge base.

As an example, the structuring of knowledge to support development of a safety case is illustrated, based very much on the definitions of the NEA but with direct consideration of the project boundary conditions set for the Japanese HLW programme. The various components of the safety case can be specified as requirements for specific areas of knowledge, which can be sub-classified into hierarchical levels – decreasing generality and accessibility to non-experts being associated with increasing level of detail. Analysis of such knowledge and its integration / synthesis to develop a safety case is, itself, also a form of knowledge which can be represented in the form of an information flow template.

The fundamental concept of the proposed knowledge management system for the Japanese HLW programme is shown for the type of safety case information flow template that would apply at the time of selecting volunteer sites to be candidates for preliminary site investigations. Much of the required knowledge base already exists; in particular, that relating to the generic assessment basis, evidence, analysis, arguments and synthesis can be mapped onto documentation produced within the H12 or H17 projects. Documentation to define the safety case purpose, context and strategy has been produced by NUMO. Nevertheless, missing knowledge can also be identified and related to goals for future site studies and supporting R&D.

The safety case knowledge base is of value to most interested audiences, but there are also additional knowledge needs that are more specific to particular stakeholders. These are explicitly listed for the implementer, regulator and other important stakeholders – which include academic and professional bodies, political decision-makers and the general public.

Based on an indication of knowledge requirements, the characteristics of an ideal formal knowledge management system (KMS) can be listed. For implementation, this could be supported by sophisticated information technology tools, which offer the opportunity to go far beyond knowledge management as currently practised in the nuclear waste management business. Although very ambitious, such powerful tools are credible, based on reasonable extrapolation of the existing state of the art over the decades until a HLW repository will be licensed for operation. Nevertheless, these need to be complemented by appropriate institutional commitment to the KMS and, in particular, a focused programme to maintain and develop the tacit knowledge represented by experienced staff.

For the particular case of the Japanese volunteer approach to siting, establishing dialogue with non-technical stakeholders will be essential to success and hence two-way communication must be a cornerstone of the KMS, working to address the asymmetry of knowledge which has often been identified as the root-cause of problems in the past. This can be addressed both formally, based on communication theory approaches, and informally by improving the user-friendliness of interfaces between the KMS and all potential users.

The report focuses on the HLW programme, but, in principle, it is more widely applicable in terms of both approach and knowledge content. The considerable challenges in implementing the proposed KMS are thus considered to be well justified by the value of the final product.

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1 INTRODUCTION

This report is based on an original Japanese document (JNC, 2005a), but does not represent a direct translation as the content has been modified to make it more easily understandable by an international audience who may not be fully familiar with the Japanese radioactive waste management programme. As introductory clarification, it should be emphasised that responsibilities for radioactive waste management vary depending on the type and source of waste involved. For spent fuel (SF) from nuclear power reactors, in particular, there is an established government policy of recycling by reprocessing (based on the principle of sustainability) and hence effort on higher activity waste is focused entirely on the vitrified residue from this process (termed “HLW” in this report). The decision to consider deep geological disposal of such waste as the only management option is also established as government policy.

The responsibility for initially developing a disposal concept for HLW and demonstrating its fundamental feasibility for the geological conditions found in Japan was allocated to JNC (previously PNC; e.g. AEC, 1976). This feasibility is established in two technical progress reports (“H3”, PNC, 1992; “H12”, JNC, 2000a, 2000b, 2000c, 2000d), the latter being used to define the legislation which established a new organisation as the HLW repository implementer and to provide the basis for establishing regulatory guidelines for such a repository.

1.1 HLW R&D after H12

Following the publication of H12, 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, NUMO has the clearly defined remit to develop a project for the safe disposal of HLW. This responsibility includes selection of the repository site, developing license applications, construction, operation and closure of the repository.

NUMO is an implementing organisation and, as indicated in Figure 1-1, operates within a network of government and private organisations which have specific responsibilities for the technical, legal, regulatory and funding activities associated with radioactive waste management in Japan. METI has responsibility for establishing basic policy and defining a 10-year disposal plan (updated every 5 years).

From the point of view of HLW R&D, the period after 2000 is characterised as a transition from a “generic” to an “implementation” phase – for which a new national programme framework has been specified (AEC, 2000). Although JNC does not now have a specific integration role, it is one of the key R&D organisations supporting the HLW project. Apart from over 20 years of experience accumulated in the HLW management field, JNC has unique R&D facilities (Figure 1-2) including:

- ENTRY: a custom-built laboratory allowing large (“engineering”) scale experiments to be carried out on both engineered barriers and representative geosphere materials, supported by extensive analytical work in conventional laboratories and computer modelling groups;

- QUALITY: a suite of "hot" laboratories allowing work to be carried out directly with radionuclides and radioactive materials – again with state-of-the-art analytical and modelling support;
- Mizunami and Horonobe URLs: purpose-built underground research laboratories (URLs) under construction in the crystalline basement at Mizunami and sedimentary formations at Horonobe, respectively.

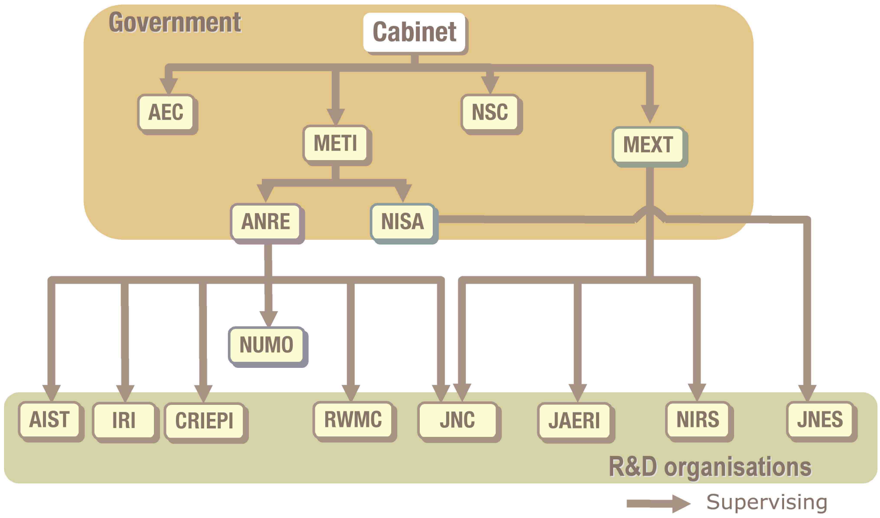


Figure 1-1: JNC in the context of the Japanese nuclear waste management programme (after NUMO, 2004c).

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)
IRI: Institute of Research Innovation (http://www.iri.or.jp/index_e.htm)

JNC is charged with further R&D to establish the safety regulation framework and to clarify specific issues related to safety assessment, geoscience and repository technology which were identified as open questions in H12 or which have been recognised as being important in terms of increasing stakeholder confidence.

An important change in the organisational structure of JNC will occur in October 2005, when it will merge with JAERI to form the Japan Atomic Energy Agency (JAEA). This new organisation will have the clear remit to provide basic HLW R&D to support all stakeholders – including not only the implementer and various regulatory groups, but also the general public.

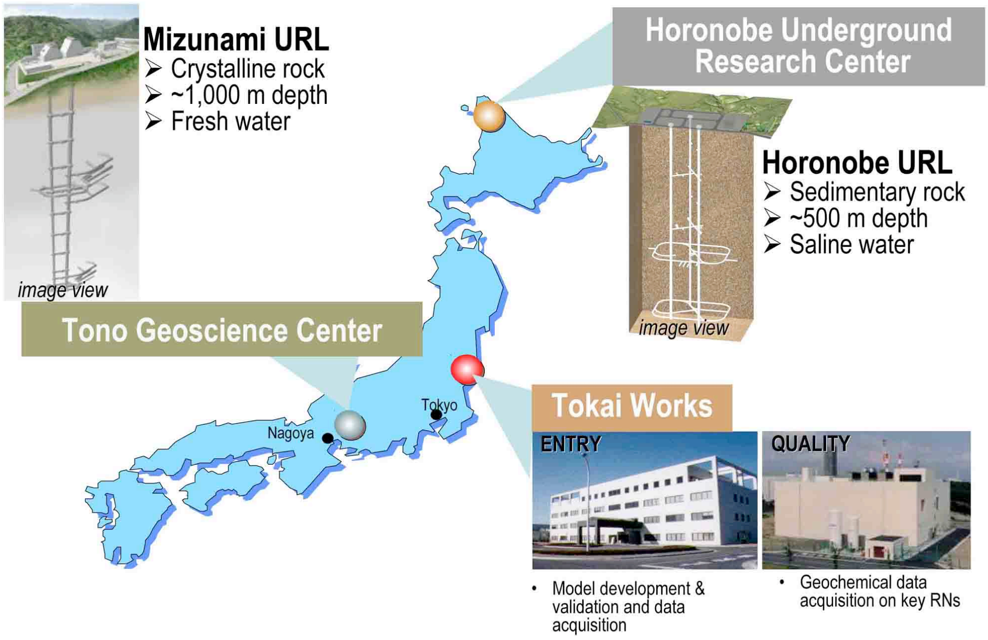


Figure 1-2: JNC R&D facilities in the context of the Japanese nuclear waste management programme.

1.2 JNC's programme of HLW R&D

Although there is a clear need for a long-term perspective in the planning of R&D to support a repository programme, detailed planning is constrained by a 5-year programme review cycle. Nevertheless, in addition to technical work specifically aimed at defined project goals, JNC recognises the importance of strategic education / training to ensure the availability of the experienced scientists and engineers required for future project phases. As such, it is considered important to include a certain amount of "blue sky" research aimed at attracting highly qualified members of the younger generation into this field and also complex, technically challenging projects (e.g. involving analogues or underground test sites) which provide unique training in the multi-disciplinary synthesis required for many waste disposal applications.

1.2.1 The current 5-year programme (2001-5)

For the present R&D programme, two major global goals have been defined:

- demonstrating the applicability of disposal technology to specific geological environments and extending from the base defined more generically in H12;
- further understanding of long-term system behaviour; integrating information from conventional laboratory studies, in-situ experiments, natural analogues and mathematical modelling to develop confidence in the predictability of the evolution of the repository and its environment over periods of hundreds of thousands of years.

For each of these goals, sub-goals have been defined which can then be related to specific work packages classified under the traditional discipline areas of geoscience, repository engineering technology and safety assessment (Figure 1-3).

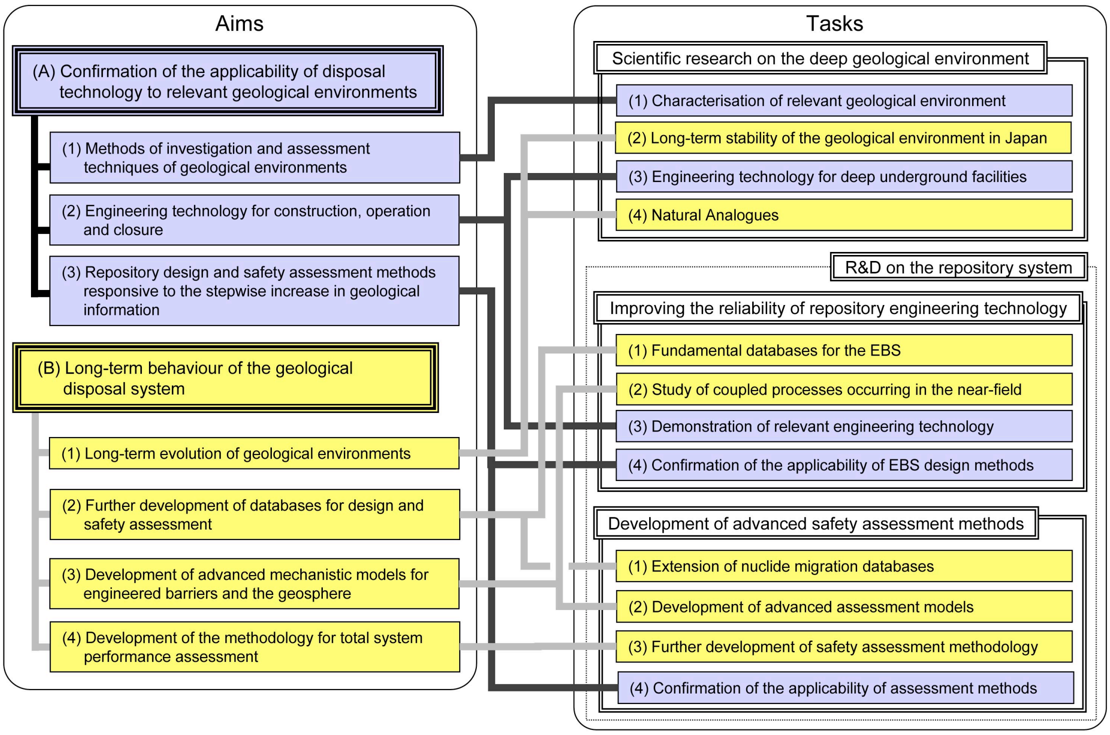


Figure 1-3: Goals of the current JNC 5-year plan mapped onto specific work areas.

In the geoscience area, research on the deep geological environment includes work carried out at the two URL sites, field work throughout Japan and collaborative projects with foreign partner organisations. Demonstration of applicable technology involves both assessment of the tools, methodology and information synthesis for characterisation of relevant siting environments and providing a basis for the engineering technology required for safe and practical construction and operation of a deep repository. Understanding the long-term behaviour of the repository system includes further fundamental studies of processes influencing the long-term stability of the geological environment in Japan (predominantly associated with its active tectonic setting) and also investigations of natural analogues – both in Japan and abroad.

In the field of repository engineering technology, effort focused on technology demonstration includes both studies of the behaviour of key materials and structures under repository conditions and confirmation of the applicability of the codes and databases used for associated repository design work. More fundamental studies to support long-term predictions of behaviour involve further understanding of key processes by using e.g. archaeological analogues and expansion of the databases of properties of EBS materials, both individually and in terms of their interactions with each other and with the surrounding rock. Such efforts are complemented by development and testing of the coupled models (and their associated databases) required to assess the behaviour of the repository near-field, particularly during early transient phases when hydrology, temperature, mechanical properties and geochemistry are all evolving in a complex manner. Alternative materials such as low-alkaline cement are also studied.

Effort in the safety assessment field has not involved carrying out total system analysis (as was the case in H3 and H12), but rather developing and testing the approaches, tools and databases required to carry out such work for specific sites in the future. Demonstration of applicability has been limited to examination of a few components of the safety assessment model chain. More extensive effort has been invested in further developing the methodology, models and databases used to quantify the long-term safety of a repository on a site-specific basis. Methodology development has included detailed examination of the significance of uncertainties associated with the formulation of volcanic perturbation scenarios and with the representations and parameters used to quantify radionuclide transport in the far-field. Model development is focused very much on improving the capability of codes to reproduce (or, in the best case, "blind predict") the results of laboratory and field tests which attempt to simulate the behaviour of particular engineered and natural barrier systems as realistically as possible. Database effort has concentrated on the compilation and evaluation of element-specific data (e.g. fundamental thermodynamic, empirical sorption) which can be used to determine the parameters that would be used to quantify radionuclide release and transport (e.g. solubilities, system-specific Kds) in safety assessments. This last effort, in particular, utilises data produced in QUALITY, which are integrated with partner databases within projects coordinated by the NEA.

1.2.2 Placing the R&D work in context

A constant challenge in any major R&D programme is keeping large numbers of very specialist studies in line with global goals. This process is helped by the integration carried out in H12, which allowed key open questions to be identified based on a total system assessment. The reporting of R&D results follows the specific structure indicated on the right-hand side of Figure 1-3, with individual reports covering each of the three discipline areas. As this structure is similar to that of the H12 supporting reports, general progress made in each area - and the extent to which open questions have been addressed - can be readily determined.

The generic basis provided by H12 does not, however, address many of the key issues which emerge in the increasingly site-specific implementation phase. NUMO has recognised this and produced technical reports which identify such issues from the viewpoint of the implementer. These are separately documented for repository concept development (NUMO, 2004a, 2004c) and site selection / characterisation (NUMO, 2004b, 2004d).

NUMO has a wide definition of a "repository concept" as "a design of all surface and underground repository structures, 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 economic and socio-political impacts**. The **concept is dynamic**, evolving with the programme as it moves from early generic studies through to siting and, eventually, licensing for construction and operation." The aspects highlighted here in bold text involve clear extensions from H12, which need to be represented in JNC's evolving R&D programme.

NUMO has selected a volunteer approach to siting (NUMO, 2002a, 2002b, 2002c, 2002d). This requires not only considerable flexibility with regard to repository concept development, but also a particularly wide toolkit of characterisation technology / experience which can then be adapted to fit any particular volunteer. In the first phase, emphasis would be on assuring geological stability – in the Japanese context a great concern which needs to be addressed in detail and clearly communicated to all stakeholders.

As shown in Figure 1-1, apart from JNC there are other organisations such as RWMC, CRIEPI, IRI, AIST and NIRS which are also promoting R&D to support government policy-making, formulation of regulations and implementation of the HLW disposal programme. On 22nd July 2005, a "Coordination Executive" was established to maximise the output from these R&D organisations, including JNC. The Executive is comprised of senior members of R&D organisations and is chaired by ANRE of METI. The regulator and its associated R&D organisations and NUMO participate as observers.

In addition to the national context, particular emphasis is placed on following international developments in the waste management field. JNC participates directly in most relevant international conferences and working groups and has taken their output into account when assessing the direction of its R&D programme. Important examples of such international developments include:

- international overview of political and technical progress in geological repository development (NEA, 2005)
- collective opinion on the environmental and ethical basis for geological disposal (NEA, 1995)
- draft safety standards for radioactive waste disposal (IAEA and NEA, 2004)
- nature and purpose of the post-closure safety case (NEA, 2004)
- reversibility and retrievability (NEA, 2001a).

1.3 Goals and structure of H17

The H17 project reports the progress made by JNC since H12 in the R&D areas supporting the geological disposal of HLW in accordance with the current 5-year programme (Figure 1-4). The three progress reports covering the geoscience, repository engineering and safety assessment fields are published in Japanese only (translations of their Executive Summaries are included as Appendices to this report), although many of the key findings have been (or will be) published in English in the international technical literature. These reports build on the equivalent supporting technical reports of H12, which have also been published in English (JNC, 2000a, 2000b, 2000c, 2000d). A key feature of the R&D since H12 is the initiation of the two ongoing URL projects, the results of which are summarised in the H17 progress report Volume 1 (English overview in Umeki et al., 2005).

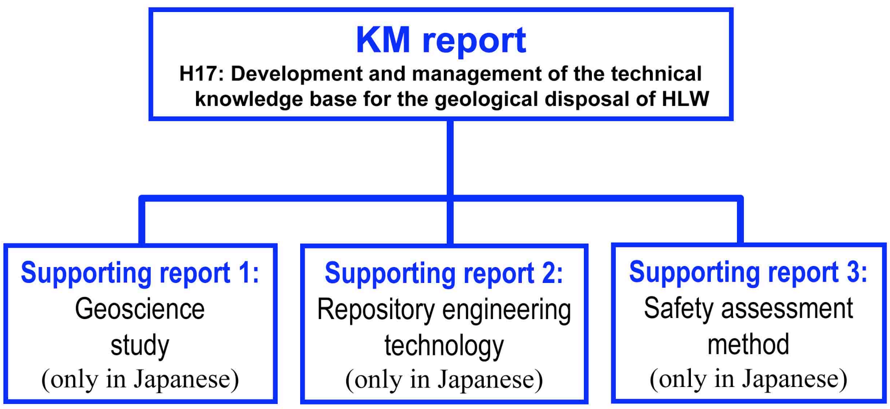


Figure 1-4: Structure of the H17 documentation.

A novel feature of H17, however, is the present knowledge management (KM) report. This is intended to introduce an approach which presents the R&D work in the context of the evolving implementation phase and which is intended to structure and prioritise future work. This is very different to the main report of H12, which was a synthesis demonstrating the basic feasibility of HLW disposal in Japan and providing the foundation for establishing the implementing organisation and associated regulations.

1.4 Purpose and structure of this report

As indicated above, this report will outline an approach to KM which will be used to structure and prioritise HLW disposal R&D activities. It will define a starting-point by its application to the basis provided by H12 and the output of R&D carried out by JNC over the last 5 years.

Chapter 2 introduces the "safety case" concept, which will be used to define the top-level structuring of the knowledge base. Although there is no internationally established consensus in this area, this chapter is based very much on the concepts and definitions derived by the NEA (2004) for the post-closure safety case, although these are amended slightly to make them more consistent and compatible with established terminology and practice in Japan. The technical content involved in making the safety case is, however, extended significantly in order to explicitly include constructional and operational safety and also important socio-economic and programmatic constraints (e.g. tailoring, optimisation).

This structure is applied to the existing knowledge base in Chapter 3. By mapping the subcomponents needed to establish a safety case against currently available knowledge, some topical areas where R&D is required can be clearly identified, even though they were not all previously identified as open questions in H12.

Chapter 4 looks into the future and outlines plans to formalise the knowledge management process by using a relational database approach. Such an approach should allow this knowledge management system (KMS) to be interfaced directly to a requirements management system (of either the implementer or a regulatory organisation) to provide a much more detailed technical assessment of knowledge requirements to guide the planning of future R&D. It is recognised, however, that meeting such formal requirements is necessary, but not sufficient. These must be extended by also considering less strictly defined ("fuzzy") needs such as those for:

- supporting other stakeholders (e.g. political decision-makers and the general public)
- maintaining staff expertise
- establishing long-term projects in advance of future needs (anticipating requirements)
- identifying potentially critical developments in science and technology which could produce new knowledge beyond present capabilities (anticipating the state of the art).

2 DEVELOPMENT OF THE TECHNICAL KNOWLEDGE BASE FOR GEOLOGICAL DISPOSAL OF HLW

Geological disposal projects are supported by, and themselves generate, huge amounts of extremely diverse information which can all be classified as "knowledge" in the terminology of this report. A key role of knowledge management is to structure this knowledge base in such a way that it can be quality assured, easily used and important gaps can be identified in order to focus the R&D which will generate new knowledge. In the past, such knowledge management has been carried out in an informal, ad hoc manner which, in many national programmes, depended on a limited number of experts with a wide overview of all relevant work. As the knowledge base expands with time, particularly for larger programmes, this becomes increasingly impractical and hence the widely recognised need to initiate more formalised management procedures. Despite a broad consensus on the importance of knowledge management, this is an area in which progress in the geological disposal field has been limited to date, although considerable efforts have been made in the related area of nuclear power generation (e.g. within the IAEA International Nuclear Information System (INIS) - http://www.iaea.org/km/cnkm/inis.html.

A critical process in the management of knowledge is the compilation and organisation of information in a logical manner. There are many different ways in which a specific knowledge base can be structured, depending on the needs of the user. Indeed, if the user has structured his requirements in a rigorous manner (e.g. using a formal requirements management system – RMS), this might automatically impose a structure on the supporting knowledge base. In the absence of such structured requirements from end-users, however, this chapter will review the generic knowledge needs for geological disposal of HLW and the particular constraints set by the approach to implementation adopted in Japan. Particular emphasis is placed on the post-closure safety case – the construction of which is a key task of the implementer and the review of which by the regulator (and acceptance by political decision-makers and the general public) will be a key component in the decisions to be made in a stepwise approach to disposal programme implementation.

The principles of structuring the knowledge base will be developed in a general manner, considering topical subdivisions of knowledge, hierarchies of increasing level of detail and the relationships between them. Application will be illustrated by expanding on the identified components on the safety case, which emphasises that the processes of information manipulation, integration and synthesis are, themselves, a type of knowledge.

2.1 Specific features of geological disposal

2.1.1 Passive safety based on a multiple barrier system

Radioactive waste management has been an increasingly important area of study for the last few decades. In addition to work in national programmes, establishing a standard and consistent framework for waste management activities has been a focus for working groups of the IAEA and NEA. It is recognised that radioactive waste disposal involves significant differences as compared to conventional engineering projects, predominantly associated with the very long timescales over which safety must be demonstrated.

The basic principles of radioactive waste management have been documented by the IAEA (1995). For the specific case of deep geological disposal – the only management option considered for HLW in Japan – the requirements for protection of man and the environment can be assured by a system of engineered and natural barriers. These barriers are passive, in that their performance is assured after repository closure without any subsequent human activity. Thus, although post-closure performance monitoring is not precluded, it is not required for the demonstration of safety.

Apart from general consistency with the IAEA principles (IAEA, 1995), a consensus on the compatibility of geological disposal with environmental protection and ethical principles has been developed as a “collective opinion” of the Radioactive Waste Management Committee (RWMC) of the NEA (NEA, 1995). Geological disposal is also consistent with the terms of the Joint Convention on the Safety of Spent Fuel and the Safety of Radioactive Waste Management (IAEA, 1997). Considerable experience with geological disposal has been accumulated for a range of radioactive wastes and, for the case of HLW (or spent fuel for direct disposal - SF), several projects are now advancing towards implementation (NEA, 1999a, 2005).

Repository projects for HLW and SF raise considerable public concern and are thus characterised by designs showing a high level of robustness – e.g. incorporating multiple, redundant barriers, siting in stable geological formations at depths which exclude perturbation by dynamic surface processes, conservative design with high safety margins, etc. Indeed, such multiple barriers lead to extremely high performance under the expected evolution of the repository system – typically no release of any radiological significance at any time in the future.

Despite such high levels of safety, public concern persists. The projects themselves are thus developed in a slow, stepwise manner in which decisions are made in an open and transparent way, allowing confidence to be built up in key stakeholder groups (see section 2.2.1).

2.1.2 Repository safety assessment and the management of uncertainties

The evaluation of the performance of geological disposal options for HLW is determined in a formal safety assessment process, which includes quantitative analysis using chains of computer models (NEA, 1991). The key role of modelling for post-closure analysis is determined by the enormous time periods over which the assessment must be carried out - typically hundreds of thousands to millions of years – which are very far beyond those that could be covered by any kind of direct performance demonstration. A modelling approach is also needed to simplify the system studied, as the large volumes of rock that represent the most fundamental barrier involved can be characterised to only a limited extent.

The models are developed and interpreted within a formal assessment procedure (Figure 2-1). The first step involves description of the system to be analysed, characterised in terms of Features, Events and Processes (FEPs). The FEP list aims to be as complete as possible, including not only likely FEPs, but also those which are in any way possible for the system under consideration. Because the repository system cannot be characterised completely and the future is inherently impossible to predict, the aim of the FEP list is to be able to capture all possible system evolutions by scenarios which are produced by particular combinations of such FEPs. It is neither possible nor useful to assess every possible combination of FEPs; the key aim in scenario development is to identify particular combinations which bound system performance, using the full FEP list to check that nothing has been missed out.

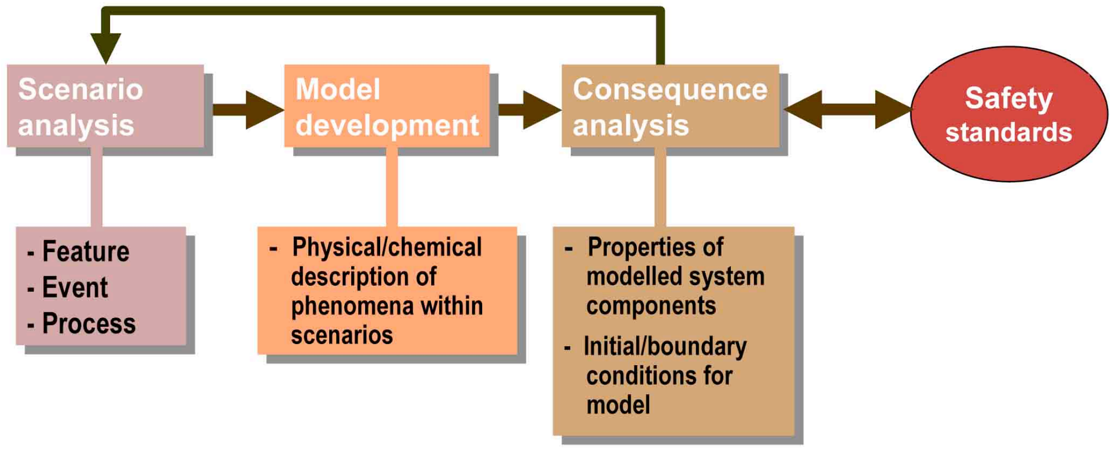


Figure 2-1: Overview of the key steps within a quantitative safety assessment (JNC, 2000).

For the selected scenarios, models are then developed which quantify the physical and chemical phenomena involved. Consequence analysis involves simulation of the evolution of the system using such models, for defined properties of the system components and specified initial and boundary conditions. The results from the consequence analysis of all relevant scenarios can then be compared to specified safety standards or guidelines.

Even though the models and databases used may be quite sophisticated, for example directly representing changes in system properties with time, they are clearly greatly simplified as compared to the actual repository system. Uncertainties thus arise in each step of model development and the analysis of these uncertainties is, itself, a key component of the assessment process. Data uncertainties can be considered, to some extent, via sensitivity analysis or stochastic approaches, while model uncertainties can be examined by considering alternative models or model variants. Uncertainties in the scenarios themselves are more difficult to assess but, to ensure that the full envelope of possible evolutions is defined, extreme (even physically impossible) “what if” scenarios may be included.

A general characteristic of repository projects is that uncertainties in the system description are very large at early stages, but decrease with time as sites become better characterised and the repository design becomes more complete. Uncertainties may also decrease due to increases in system understanding as a result of general scientific progress. Safety assessments are thus carried out repeatedly in a stepwise implementation programme, with feedback to the supporting site characterisation and repository technology programmes, to allow iterative improvement of confidence in the assessment output.

For the sake of completeness, it can be noted that the same basic approach can be taken to assess safety during construction and operation, but here logging of incidents allows the validity of the assessment to be evaluated directly and provide iterative improvement of both construction / operation procedures and the associated assessment approach.

2.2 Geological disposal programme implementation

Geological disposal projects worldwide have been characterised by delays and disruption due to public concern and lack of political support. To counter this, two marked trends have been noticeable over the last decade or so – development of more gradual, staged approaches to project implementation and broader approaches to the demonstration of system safety.

2.2.1 The stepwise approach and associated decision-making

In response to public concerns, ethical aspects of geological disposal projects have received more extensive consideration in recent years (e.g. NEA, 1995, 2005; IAEA, 1995). In particular, it was recognised that such projects - which perform a national (or international) service and have a perceived associated long-term risk - give rise to issues of intra- and inter-generational equity.

Because the benefits of nuclear power are widespread but geological disposal projects are localised, there has been a common NIMBY (not in my back yard) response from the communities around potential sites. This strong response is emphasised by the long duration of repository projects (many decades between initiation and final closure) and the even longer periods over which there is a perceived health hazard. Despite the technical consensus on the high level of post-closure safety, this is generally not well understood by non-specialists.

A further ethical concern arises from the perceived irreversibility of the decision to initiate a disposal project (e.g. KASAM, 1988). This is seen as restricting the rights of future generations to change their minds about the choice of disposal as a waste management option. Although some of the arguments involved are associated with optimising use of resources and the principle of sustainability, which are more relevant to SF than HLW, there is clearly a dichotomy between maximising choices available to future generations while ensuring that burdens associated with the implementation of waste management projects are borne by the generations benefiting from the power produced.

The critical problem, however, can be traced to the discrepancy between the technical consensus on the feasibility and safety of geological disposal (NEA, 1999a) and the level of public concern. One way to improve this situation is to develop repository projects in a slow, stepwise process, which allows time for the communities involved to develop understanding of the technical issues and confidence in the implementing and regulatory organisations.

To be effective, however, it is recognised that this stepwise approach should have a number of specific characteristics:

- An active programme of communication with all interested parties which focuses on dialogue to clearly identify the main concerns involved and the progress being made towards addressing them.
- A clear, transparent decision-making process at the end of each stage, ideally with direct involvement of all key stakeholders.
- Specific options for reversing decisions to respond to new technical knowledge or changing socio-political boundary conditions.
- Flexibility to amend concepts to respond to public concerns (e.g. including monitoring, eased reversibility / retrievability), even if these do not appear to be technically justified.

The individual stages can be defined by obvious project milestones, e.g. literature studies and concept development, preliminary characterisation of sites, final site selection, licensing, construction, operation and closure. Due to practical constraints, these individual milestones may be separated by many years – or even decades – and hence further sub-stages may also be defined. The exact form of the programme would, however, depend on the prevailing socio-political conditions in the country involved.

This stepwise implementation process may also be seen as positive from the viewpoint of the supporting technical programme. Iterative site characterisation, design and safety assessment at each stage can provide feedback to improve the focus of R&D and allow the repository design to be tailored to the site. Such evaluation cycles need not stop with initiation of repository operation, but can (and should) continue to allow experience gained to be utilised for further optimisation.

Although focused on specified technical requirements, the R&D programme should also involve continuous dialogue with non-technical stakeholders to ensure that their particular needs are adequately addressed. As HLW repository projects are currently "first of kind" facilities, the entire repository system cannot be illustrated and there may be a need for specific long-term, realistic demonstration experiments aimed, at least partially, at lay audiences.

A particular example of a detailed evaluation of siting (NRC, 2003) is provided by the US National Research Council (NRC) consideration of the process of construction, operation, closure and post-closure phases of the repository for SF and HLW planned for Yucca Mountain. After consideration of a more conventional "linear" form of staging, which represents stepwise implementation of a fixed project plan, a more flexible "adaptive staging" process was recommended. The latter places special emphasis on project re-evaluation at the end of each stage, with the specific options of being able to reverse past decisions, repeat stages and modify the project in the light of new knowledge being explicitly considered. Such adaptive staging is consistent with international thinking – e.g. with regard to reversibility and retrievability (NEA, 2001a).

2.2.2 Stepwise implementation in Japan

The phased process of developing a siting project, involving more detailed characterisation as options are narrowed down, is outlined in Japanese legislation (the Specified Radioactive Waste Final Disposal Act – see section 1.1). NUMO, following extensive discussions with many stakeholders, decided to take a rather innovative approach to the siting process. Based on consideration of international experience in repository siting, local acceptance was identified as a critical issue which is essential to the success of such projects and hence a policy of calling for volunteers to host this facility was adopted (NUMO, 2002a, 2002b, 2002c, 2002d). The resulting development programme for a first HLW repository is outlined in Figure 2-2. This is based on an assumed capacity of 40,000 waste packages, 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, 2000a). According to the Final Disposal Plan (MITI, 2000b), repository operation could start as early as the 2030s, with an annual emplacement rate of 1,000 canisters of vitrified HLW.

Following the 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 volunteer site in the light of the exclusion criteria and to help to determine the overall practicality of the project and, eventually, to discriminate between potential repository locations.

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 number (one or more) 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 around 2035. The time plan shown in Figure 2-2 assumes that, to some extent, construction, waste emplacement and sealing of emplacement tunnels proceeds in parallel and emplacement operations are completed by mid- to late-2070s. A period of institutional control is possible, with final closure being some time after 2080.

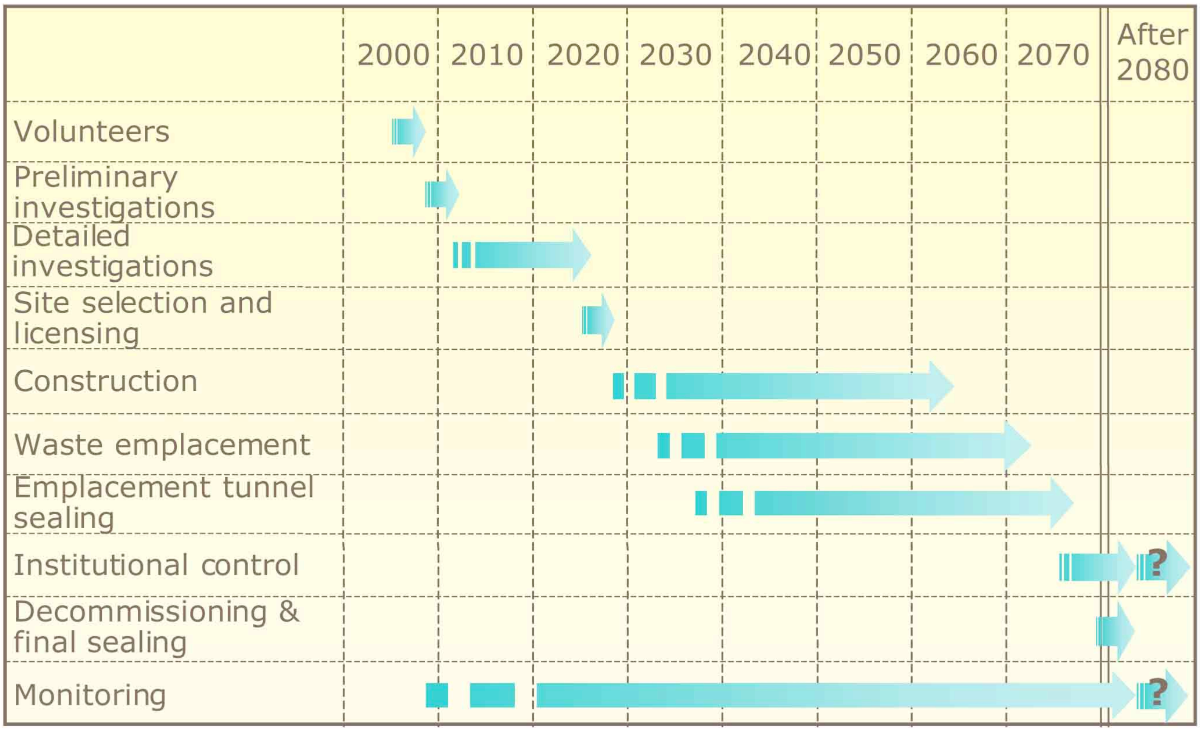


Figure 2-2: The staged repository development programme and possible milestones. The time plan after site selection has a model nature as it will depend, to some extent, on the repository concept selected (NUMO, 2004c).

2.2.3 The role of R&D

As noted above, the stepwise approach is based on continuous improvement of system understanding to support the decision-making process, which needs to be reflected in an appropriate R&D programme. Key siting and licensing decisions may require a safety case to be made (see section 2.2.4 below), which has its own specific R&D needs.

Developing an integrated R&D programme, which will provide practical support for repository implementation while increasing confidence in the safety case by reducing important areas of uncertainty, must take special consideration of the very long timescale involved between project initiation and the final closure of a repository (in the order of a century or so). The need to concentrate effort on input immediately needed for the current project phase has to be balanced against anticipation of future needs if the information or experience required will have a long lead time – e.g. the robust engineering technology required for repository operation or the long-term demonstration projects which might be needed to confirm components of the safety case at the time of licensing. Research focused on specific project goals may also need to be combined with more fundamental studies, generally intended to maintain understanding at the state of the art, which is part of establishing technical credibility. Finally, the importance of maintaining resources of experienced manpower needs to be reflected in the plan, explicitly identifying studies which will attract future generations of highly qualified staff and will provide them with the multi-disciplinary experience required for many of the essential coordination roles in such a programme.

The resulting R&D plan should emphasise flexibility to respond to both changes in the repository programme (e.g. caused by inherently unpredictable changes in socio-political boundary conditions) and to the rapid advances in fundamental science and technology. It will also identify critical infrastructure, such as facilities for studying the behaviour of radionuclides and underground test facilities, which provide a unique opportunity for developing and testing the science and technology needed for geological repositories (e.g. NEA, 2001b).

It can be useful to distinguish R&D which is specifically associated with the practicality of repository implementation from that which contributes to more fundamental understanding of the disposal system. The latter, if it can be produced by an independent body in a fully quality assured manner, can serve as a common resource for both the implementer and the regulator.

To maximise its usefulness, therefore, the R&D programme should:

- be structured to make the purpose of individual projects clear;
- be comprehensively documented;
- be fully quality assured;
- have a clear process for identifying and managing uncertainties;
- be accessible to all stakeholders.

Uncertainty management is particularly important in the case of use of the R&D by different stakeholders. Basic information on processes and parameters may be agreed by all involved, which focuses debate on the justification of the safety case onto the interpretation of such uncertainties. It must be accepted that differences in opinion may not be resolvable even over the long time period involved and thus the safety case must simply reflect this fact of life.

Scientific R&D in general, and the discussion of uncertainties in particular, is very difficult to communicate to lay audiences. Nevertheless, efforts must be made to present important information to the general public in a way which clearly and honestly makes them aware of the issues involved. Full use should be made of print and electronic media for this purpose but, based on international experience, it is recognised that special demonstration experiments can play a key role here – particularly if directly carried out in a deep geological setting within URLs.

2.2.4 The safety case: general concept, purpose and meaning

(1) Safety case definitions

As emphasised above, the demonstration of safety is a critical component of gaining acceptance of a repository project. Formal safety assessment, as outlined in section 2.1.2, is necessary, but recognised as not being sufficient to meet the needs of all stakeholders. A much wider demonstration - termed the safety case - is required. This safety case evolves with the project in a way which is compatible with the process of staging considered in the previous section. The safety case is thus an important factor considered in the decision-making at the end of each stage, evaluating:

- whether the demonstration of safety is sufficiently convincing to justify progressing to the next stage;
- what actions need to be taken to reduce residual uncertainties so that this case will be strengthened during the following phase.

It should be emphasised that, although this terminology and concept is widely used (both within and outside the radioactive waste community), nomenclature is not standardised and there is no consensus on the exact composition of the safety case and how it should be documented. Even when considering only post-closure safety, a range of definitions have been proposed over the last few years – for example (NEA, 1999b):

> "… a collection of arguments, at a given stage of repository development, in support of the long-term safety of the repository. 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."

It is certainly debatable if a safety case can contain "unresolved issues" and, here, terminology such as "conditional safety case" might present a clearer picture.

The post-closure safety case must include consideration of construction and operation, at least to the extent that these processes affect evolution of the system after closure. This can, in principle, be extended to include a full safety case for the pre-closure period using the same basic approach (e.g. Vieno and Ikonen, 2005).

Pre-closure safety, like safety in other nuclear facilities, is assessed up to a fixed end point – repository closure. The problem with post-closure safety is that there is no such defined end point and there are major differences between different national programmes on how long safety needs to be assessed and what kind of yardsticks should be used for these periods (e.g. recent EPA evaluation, EPA, 2005). Nevertheless, in all cases, the time periods specified for demonstration of HLW repository safety are huge (from tens of thousands of years to "all time") and thus present a challenge which is unique.

A further view of the safety case is derived from the NRC (2003):

> "… to mean the integrated collection of all arguments that the implementer produces to demonstrate safety of the repository to all interested parties. Iterative assessment of the safety case is the fulcrum around which decisions are made."

Here the active role of the safety case in guiding decision-making by the implementer is emphasised.

In the most recent consideration of the post-closure safety case by the NEA (2004), reference is made to the IAEA definitions given in Box 1, indicating that these are slowly tending to be favoured internationally. Certainly they are very general and can be directly applied also to the pre-closure phase.

Box 1*:* Definitions of safety assessment and the safety case
From IAEA/NEA Draft Safety Requirements for Geological Disposal, DS154, 2004[6].

Safety assessment is the process of systematically analysing the hazards associated with the facility and the ability of the site and designs to provide the safety functions and meet technical requirements.

The safety case is an integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the geological disposal facility.

Safety assessment is a more restricted process and, as indicated in the IAEA definition, does not start from an assumption of safety. It should be an objective evaluation, on the basis of existing knowledge, of potential hazards resulting from the inevitable, gradual degradation of a repository system. It is a key component of the safety case, which should support the argument that a particular repository design at a specific location will not result in unacceptable detriment to man or the environment. Such safety should be assured without any requirement for active control or monitoring following closure.

Within a repository project which is developing in a stepwise manner, the safety case is expected to become more comprehensive and rigorous with time, in order to support decisions which generally increase in significance in terms of the commitment of resources involved. As such, the requirements become sequentially stricter to show that:

- the evaluation of the project is reliable;
- the goals of a particular stage have been achieved;
- all open questions have been identified and procedures to address them are in hand.

Some project stages will end at points which require formalised decisions, e.g. in the form of permits or licences. Licences to construct, operate or close a repository will, in general, be granted only on the condition that the implementer has produced a safety case that is accepted by the regulator as demonstrating compliance with applicable standards and requirements – and, increasingly now, is also convincing to the general public. To meet such goals, the safety case has to be presented in the form of a structured set of documents. Building a safety case that is adequate for repository licensing is a complex task that requires significant commitment of resources as compared to less detailed technical evaluations and safety assessments which may be adequate to support internal planning and decision-making. Nevertheless, the discipline of preparing a safety case, and presenting the case for scientific and technical review, regulatory review or wider non-technical evaluation by the general public, ensures that safety is explicitly and visibly considered at critical project stages.

(2) Structure of the safety case

The aims and content of safety cases depend very much on the practical and programmatic constraints on particular projects (NEA, 1997). Different repository concepts and different siting environments may lead to very different arguments to support safety and these arguments may change with time as a project advances. Nevertheless, the components of the safety case can be generally structured as indicated in Figure 2-3 (NEA, 2004).

(i) Purpose and context

The purpose and context of the safety case should be clearly documented. This identifies the background to the step or decision point within the programme for which the safety case is built. This establishes the context in which the required strength of the safety case and the importance of remaining uncertainties can be judged.

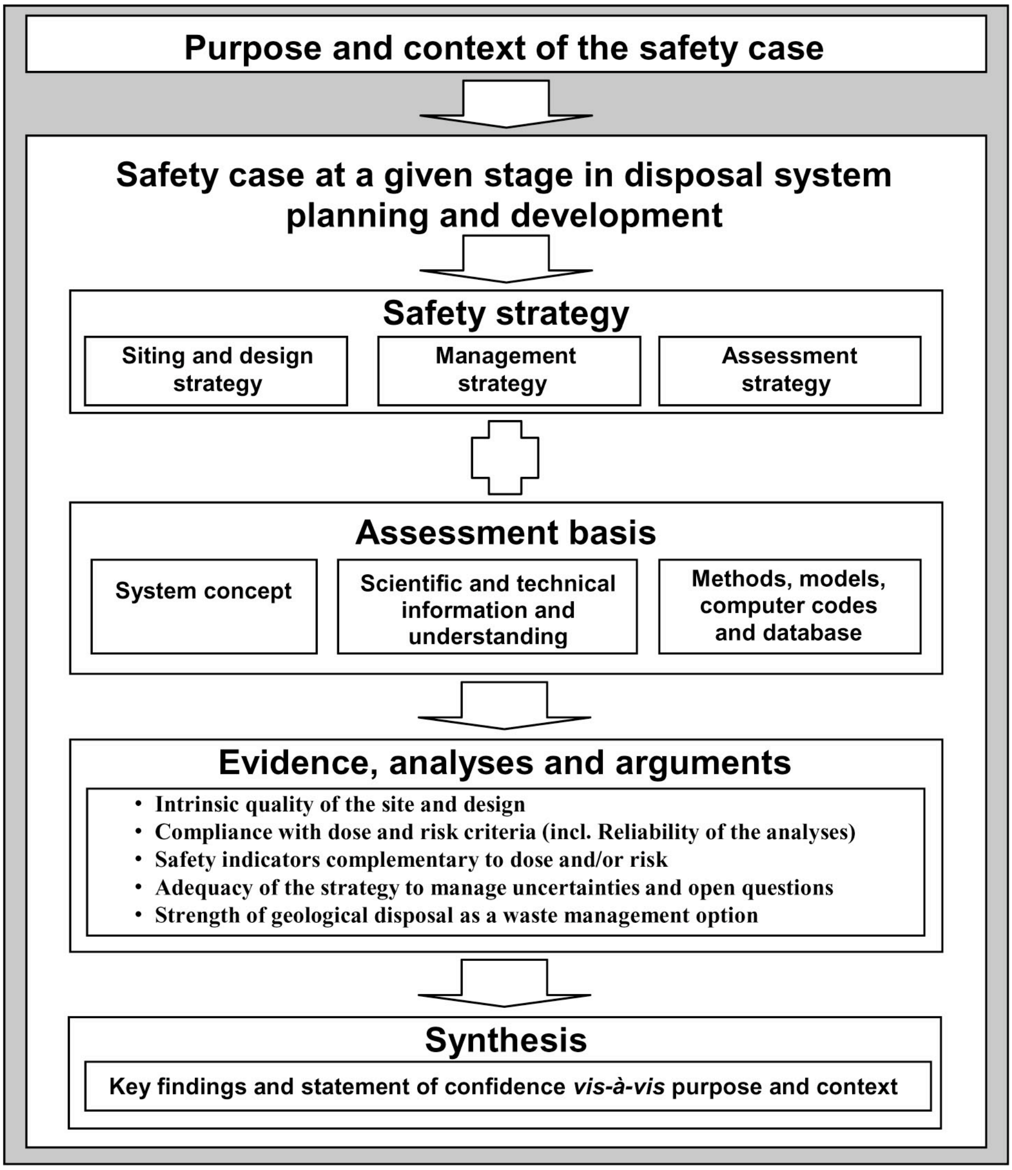


Figure 2-3: Overview of the relationship between the different elements of a safety case (NEA, 2004).

(ii) Safety strategy

The safety strategy is the high-level integrated approach adopted to ensure safe disposal. It includes strategies for site selection, design and implementation, which are tied to development of a safety case that is adequate to satisfy the needs and expectations of decision-makers at any project stage. An important component of these strategies is the management of uncertainties, e.g. compensating for these by conservatism, robustness, redundant multiple barriers (see section 2.1.1), etc. Also to be considered are non-technical programmatic uncertainties, which are inherent in planning projects over such long timescales.

Demonstration of the adequacy of the safety strategy for achieving project goals is itself a part of the safety case and should be included in the safety case documentation. A key part of this demonstration, however, involves showing the capability of organisations and staff, which can be done formally to only a limited extent (e.g. quality certification), but includes less qualitative establishment of credibility and a clear safety culture.

(iii) Assessment basis

The assessment basis includes all information and analysis tools supporting the safety assessment. This includes a complete description of the disposal system (that consists of the chosen repository and its geological setting), along with the scientific and technical data and understanding needed for evaluation of system safety. As noted in section 2.1.2, quantitative assessment of post-closure safety will require a modelling approach, so the assessment methodology, models, computer codes and databases are key components of this basis. The quality and reliability of a safety assessment depends on the quality and reliability of the assessment basis and the latter should thus be supported by convincing evidence and arguments in any detailed presentation of the safety case.

(iv) Evidence, analyses and arguments

Most national regulations specify safety goals in terms of dose and / or risk limits. Most safety cases, and all that will be subject to regulatory review, will evaluate these indicators, using mathematical analyses and/or more qualitative arguments, for a range of repository evolution scenarios. As indicated in section 2.1.2, this analysis would be carried out using a formal safety assessment methodology and would be fully documented.

The safety assessment produces not only total system performance measures, but also allows the performance of individual engineered and natural barriers to be evaluated. This evaluation can become more rigorous, with reduced uncertainties, as the project advances and the properties of these barriers become better defined. In turn, information on barrier performance and its sensitivity to particular characteristics can be fed back to the site characterisation and repository engineering teams as part of an iterative process of programme optimisation. In a staged programme, evidence of this optimisation should be presented at each major milestone.

Robustness of the safety case is strengthened by the use of multiple lines of evidence, leading to complementary safety arguments that may compensate for shortcomings in any single argument. Complementary arguments in support of a case for safety include general evidence for the strength of geological disposal as a waste management option, evidence for the intrinsic quality of the site and design (e.g. natural analogues) and safety indicators complementary to dose and risk (e.g. fluxes and distributions of radionuclides between barriers). A case also has to be made to demonstrate the adequacy of the strategy applied to manage uncertainties and open questions.

(v) Synthesis

In general, a safety case would argue that there is adequate confidence in realising a safe repository to justify a positive decision to proceed to the next stage of planning or implementation. This is a statement of confidence on the part of the producer of the safety case - typically the implementer - based on the analyses and arguments developed and the evidence gathered. The reviewers of the safety case must decide whether they are convinced that the reasoning presented is adequate and hence whether they accept the safety case. To assist the reviewers, a synthesis of the available evidence, arguments and analyses is valuable. This should convincingly justify the decision for the project to proceed to the next stage, which tacitly includes both acceptance that all goals for the present stage have been reached and that plans for future stages are adequate.

As indicated previously in the discussion of definitions, at early stages of the programme there may be considerable uncertainties in both the site characteristics and the performance of any specific repository at such a site. This may mean that the safety case must be accepted as being provisional and based on certain explicit assumptions by the implementer. The regulator thus needs to determine if these caveats are reasonable and whether there are grounds for confidence that these would be clarified in later stages of the project. This can lead to acceptance of the safety case being conditional, associated with specific requirements for future clarification.

“Confidence” in a safety case is inherently a more qualitative (or “fuzzy”) attribute than formal compliance with regulations. Compliance needs to be demonstrated at formal licensing stages, but confidence in the safety case – by all key stakeholders – is required throughout the programme. At a very simple level, confidence is enhanced by clear and logical structuring of the arguments which lead to the conclusion that the project is safe.

The arguments themselves must be convincing, even though they acknowledge all uncertainties involved. If some barriers are poorly defined, the multiple lines of evidence (empirical, theoretical, analogue, etc.) which provide strong support to others need to be emphasised. In an adaptive structured approach to staging, for example, this could involve over-engineering the EBS at early project stages, with planned optimisation occurring later in the programme. In practice, especially in a strongly staged programme, it is evident that the safety strategy and the synthesis of the safety case evolve iteratively, with the strategy being focused on ensuring that the safety case presented will be acceptable to all stakeholders at each key project decision point.

Documentation of this safety case synthesis needs to be tailored to the various audiences involved. This may require a hierarchy of documentation at different technical levels, but it is important that the basic arguments and their structuring remain consistent to avoid risk of confusion. The fundamental characteristics which are involved include:

- Transparency

  All elements of the argumentation should be developed in a clear, logical and unambiguous manner which can be easily understood by the audiences involved.

- Traceability

The sources of all key information used in documents should be clearly referenced and these references should be easily accessible to interested readers.

- Openness

  Documentation should be freely available to all stakeholders, including the general public. Even though it is inevitable that some information may be highly uncertain at early project stages or have commercial or political sensitivity, as a general principle all information used to support the safety case should be available on demand.

- A clear review process

  Both internal and external technical review processes should be established to build confidence in the technical quality of background information and the consistency of the arguments developed with the current scientific and technological state of the art.

(3) Reliability of the safety case

As a critical starting-point for the development of a safety case, the organisation producing it should have a well established consensus that the project is, indeed, safe. This can be challenging for larger organisations, particularly given the wide diversity of technical disciplines required to select and characterise a site, develop appropriate repository designs and assess their safety. It is thus important that the safety assessment teams, in particular, provide feedback to those who supply them with information to ensure that these suppliers see their work in context and appreciate its significance for the safety of the project.

Identification of the processes and parameters which have most significance for safety is fundamental to initiating safety case development. To a significant extent, this may depend on the expert knowledge of senior staff, but this can be complemented by formal methods such as sensitivity or uncertainty analysis.

Managing uncertainty is essential for repository projects. As noted previously, such uncertainty may define the assumptions on which a provisional safety case is established during the early stages of a project. A well defined process is required to ensure that efforts are made to reduce key uncertainties, at least to the extent that the top-level argument that the project is safe can be assured to be valid.

Overall reliability of the safety case cannot be decoupled from the quality of the supporting scientific and technological understanding which is, in turn, a product of the underlying R&D programme. Expected characteristics of such a programme include:

- comprehensive planning, to ensure all key issues are addressed;
- flexibility to respond to novel developments, particularly in view of potentially large changes in the understanding of important site characteristics as the project develops;
- effective utilisation of all available resources to improve understanding – e.g. combining conventional laboratory, in-situ URL, modelling and analogue approaches;
- full documentation within a formal and strictly enforced quality management system (QMS).

Quality management is accepted to be very challenging, particularly as applied to fundamental scientific research. Nevertheless, it is important to ensure that all data which may be used to support the safety case reflect the state of the art and are produced according to quality guidelines, even though conflicts may arise – e.g. with practical constraints for field characterisation studies carried out under tight time and budget constraints. The processes of deriving "upper-level" information of the type used directly in safety assessments from raw data also need to be clearly defined and auditable.

The assessment methods, models, computer codes and databases must also be clearly and logically documented. Arguments for their reliability will involve the associated QMS, which should ensure that:

- the approach is logical, clear and systematic;
- the assessment is conducted within an auditable framework and that such auditing is effective;
- the approach is being continuously improved through an iterative process;
- the approach has been subject to appropriate levels of peer review;
- effective communication is established between those engaged in research and site investigation programmes and the safety assessors;
- sensitivity analyses have been carried out to ensure that scenarios and calculation cases address all uncertainties significantly affecting repository performance;
- suitable criteria have been developed for the exclusion or inclusion of features, events and processes (FEPs) to define scenarios for evaluation;
- features, events and processes (FEPs) to be included in the assessment are audited for completeness against international FEP lists (e.g. NEA, 2000);
- evidence supporting the choice of scenarios, models and data comes from a wide range of sources, including field, laboratory and theoretical studies, and multiple lines of argument are, where possible, made to support the choice of particular scenarios, model assumptions and parameter values;
- mathematical models are based on well established physical and chemical principles, or on empirical relationships with an experimental basis that supports their applicability in conditions (e.g. scales of space and time) relevant to the assessment;
- computer codes are developed in an auditable manner; being rigorously verified (for example by comparison with analytical solutions and alternative codes) and validated (e.g. by simulation of experiments and natural analogues) to the extent possible;
- a clear strategy and methodology for uncertainty management exists.

2.3 The science and technology of geological disposal in a knowledge management context

2.3.1 Knowledge management for decision-making

In section 2.2, the needs for various types of data, information and experience have been outlined and the planning of the R&D programme to meet such needs discussed. Deep geological disposal of HLW in Japan would, however, involve a first-of-kind facility which poses novel challenges. In particular, the transferability of experience from conventional construction projects is quite limited. Normally, such construction projects result in a well defined product or piece of hardware which can be manufactured using technology which has developed gradually over a period of time and which can be quality assured and tested to achieve confidence that it meets specifications or even remediated in the case of problems. Although such a process might be partially applicable to a component like an overpack, it is certainly not to the entire repository system, which must perform safety functions over millennia as a result of many engineered and natural barriers working together. Some of these barriers may be inherently impossible to monitor or fully characterise. Certainly, the total system cannot feasibly be monitored over even a fraction of this time period and, in most cases, remediation would be impractical.

In order to address this problem, it is proposed to use a formal approach based on existing knowledge management schemes. In this particular case, "knowledge" is taken to be the global term which encompasses all of the science and technology (implicitly including social science, economics, medicine, etc.) which underpins a repository project. This can be classified as common knowledge (e.g. that established in component disciplines – geology, chemistry, materials science, civil engineering, etc.), generic waste management knowledge and project-specific knowledge – but all types must be available to develop a successful project. It is also important to note that knowledge includes not only the "explicit" information which can be rigorously documented but also the "tacit" understanding and experience which exists within expert manpower.

The term "knowledge management" (KM) will be used in this report to cover all aspects of the development, integration, quality assurance, communication and maintenance / archiving of knowledge – including data, information, understanding and experience. It is an active process, which is focused by specific programme or project requirements (themselves developed and structured by a requirements management system). Knowledge is not static, but evolves with time in line with the general progress in science. In addition, experience is associated directly with individual staff and accumulates with time. Nevertheless, an active programme of experience transfer is needed to ensure that it is passed to younger generations as older staff retire (an acknowledged concern throughout the nuclear industry and the driver for initiatives like the ITC (www.itc-school.org)).

Ideally, knowledge should be objective and value-free but, in practice, it is inevitably conditioned by the opinions of the expert staff involved and their cultural environment – particularly in areas that are novel or involve interactions between several technical disciplines. An important aspect of knowledge management, therefore, involves the evaluation of potential biases, in addition to more standard assessment of conceptual and data uncertainties.

For JNC and hence JAEA, KM aims to provide a common resource which is applicable to the needs of, and accessible to, all involved stakeholders. A particular challenge is identifying gaps in knowledge and carrying out the R&D required to fill these (a process of "knowledge creation"), given the long lead time which may be involved in many cases. To ensure that the required knowledge is available when the need arises, it may be necessary to complement existing requirements lists by attempts to anticipate future requirements.

KM involves considerable manipulation of inputs from a diverse rage of sources to produce a structured "knowledge base". The structuring takes into account not only the end use of this knowledge but also the appropriate technical level for the user. This is particularly challenging, as involved stakeholders include not only regulatory and implementing organisations, but also academic and professional bodies, politicians and the general public.

To be useful, the knowledge base has to be clearly structured. An effective way of doing this is to relate it to the desired use involved, specified as a "requirement". For any project, a hierarchy of requirements, which develop in time, can be derived directly from a project or business plan. If this is done formally in a requirements management system (RMS), this will automatically structure the underlying knowledge base (Figure 2-4). The basic principle is that the development of a project can be structured in the form of a decision network. Each decision is the result of a specific requirement and can be made on the basis of knowledge and the output from previous decisions. The concept is rather obvious in theory – the question is can it be implemented in practice?

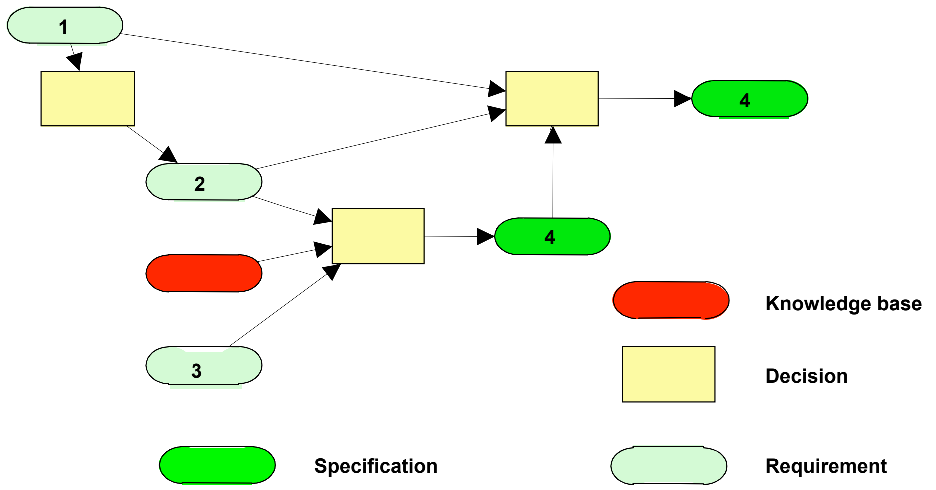


Figure 2-4: Idealised representation of a decision network, indicating a sequence of formal requirements which lead to decisions. Some early decisions may be predominantly political (e.g. setting boundary conditions for the NUMO programme – HLW only, geological disposal in Japan at a depth greater than 300 m, etc. (NUMO, 2004c)), but subsequent decisions become increasingly technical, requiring support from an appropriate knowledge base.

Although the novel aspects associated with geological disposal projects have been emphasised previously, the general problem of managing huge data and information flows in complex, long-term projects in the face of technological change and evolving socio-political boundary conditions is not unique. A good example here would be the aerospace industry, where requirements management systems have proven invaluable in projects where planning may last 2 – 3 decades and subsequent operational lifetimes could be double this. The number of components and processes involved in the construction and operation of a large aircraft may lie in the millions - and many of these may have significance for safety. Despite the high profile given to accidents, the very good safety record of the civil air industry in a challenging environment provides sound evidence that the problem is solvable.

The concept proposed thus includes:

- a formal RMS, to guide and document the decision-making process;
- a coupled knowledge management system (KMS), to ensure that all knowledge needed to support these decisions is available as and when required;
- an associated system to assure quality (QMS), possibly with integrated documentation management.

This would be compatible with the principle of defining a clear and transparent process for safety case development, as discussed previously (NEA, 2004). This has already been recognised by NUMO, who plan to implement such management systems as part of their structured approach to repository implementation (NUMO, 2004c; Kitayama et al., 2005).

It is clearly the responsibility of the end user to specify his requirements. It should be emphasised that the decisions to be made by the regulator and implementer are inherently different and hence their requirements, and the form of any RMS they produce, would also differ. This would be the case even if the fundamental knowledge base required may be similar – or even identical in some cases. For example, the implementer must consider the expected "nominal" evolution of the project in detail, with emphasis on practicality of construction and operation – aiming at optimisation and ensuring that budget and throughput targets are met. These aspects are of less interest to the regulator, who is more concerned with operational perturbations and the way in which these affect safety - and also non-safety environmental impacts.

Compared to other industries, the highly sensitive nature of waste disposal means that there is also a strong requirement for communicating knowledge to the concerned general public. This should not, however, need a separate RMS, as such communication should be clearly required by both the regulator and the implementer. However, in cases where specific aspects of a project may be presented differently by the regulator and implementer – or indeed other groups of project proponents and opponents – the producer of the KMS may be specifically required to review the state of the art, distinguishing between hard facts and differences in opinion in a strictly neutral manner.

To perform these diverse roles, the knowledge base and the associated KMS should ideally have the following attributes:

- Content: comprehensively covering all knowledge required by all stakeholders, which may necessitate timely initiation of work in anticipation of future requirements;
- Autonomic maintenance: allowing constantly expanding external databases to be utilised in a data mining process;
- Reliability: fully quality assured with automatic processes to ensure the consistency of the expanding knowledge base;
- Active initiatives to keep both the content and the KMS structures at the state of the art;
- Openness and accessibility to all stakeholders, at technical levels appropriate to their needs;
- A robust process for ensuring the long-term conservation and archiving of knowledge of all types.

If JAEA is established as the operator of the central KMS, its clear independence has to be assured, along with the availability of the resources to carry out this work. As a first step, past studies which provide the technical basis for the current stage of the disposal programme should be analysed to determine the requirements and knowledge used to establish the background constraints resulting from past decisions.

2.3.2 Structuring the knowledge base using a safety case concept

In the absence of a documented set of structured requirements by either the regulator or the implementer, the process of structuring the knowledge base will be illustrated using the example of the safety case as specified in section 2.2.4 above. This is reasonable, as development of a safety case to support selection of Preliminary Investigation Areas (PIAs) (NUMO, 2004d) will be an imminent task for NUMO and this selection process will then need to be reviewed by regulatory organisations. If it is associated with assessing acceptability of volunteers, such a safety case will also create significant public interest.

As defined previously, the safety case includes a number of components which are related to each other in a structured, hierarchical manner (Figure 2-3). These components, in turn, contain structured sets of activities – although in some cases the boundaries involved are rather fuzzy, due to the difficulty of being precise in a generic description which should apply to projects with different boundary conditions and at different stages of development. Nevertheless, such structure is sufficient to serve for demonstration purposes. In any case, as the knowledge base is examined in detail, further structure naturally emerges – for example as set by the differentiation between the different disciplines (chemistry, physics, geology, engineering, etc.) and the approaches (field observation, experiments, mechanistic modelling, analogues, etc.) producing the source information. A pragmatic distinction will also be made between "international" knowledge produced by – or in collaboration with – partner organisations and that resulting from the Japanese national programme (NB generally only the latter can be fully subjected to Japanese QM procedures).

The hierarchy of knowledge supporting the safety case is illustrated in Figure 2-5. At the top level is the claim that the system is safe, subject to any specific caveats relevant to the stage reached, as it would be from the viewpoint of an implementer (for a regulator, this top-level claim would be that the safety case and caveats are acceptable to allow progress to the next programme stage – maybe with specific riders attached). Below this claim lie an ordered set of argumentation components which provide the basis for a sequence of decisions. The knowledge base provides input to each of these decisions and such input may itself be structured in a number of layers of increasing technical detail before the base of fundamental measurements and theoretical knowledge is reached. The process of integrating "lower-level" knowledge to produce knowledge at a higher level involves some kind of synthesis, which can be generally classified as "inference rules" (even if often, in real life, this may result mainly from expert opinion).

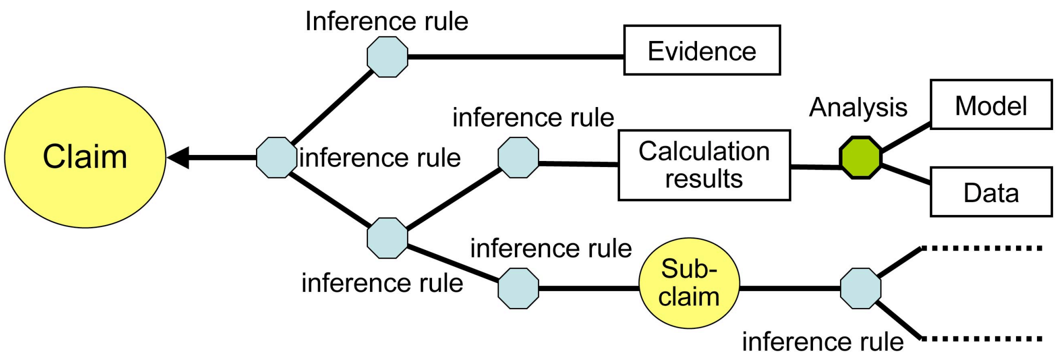


Figure 2.5: The hierarchy of knowledge supporting a safety case (see text for explanation).

The basic principle of such structuring is illustrated in Figure 2-6. In any particular area, total knowledge can be grouped into sets – for example information provided by different technical disciplines. These can be related to each other by single- or double-headed arrows, depending on whether links between them are one-directional or associated in a more complex manner.

For example, if knowledge set i represented site hydrogeology, set j might be site topography – which clearly influences hydrogeology but is not, itself, directly affected by any aspect of groundwater flow. On the other hand, set k could represent hydrochemistry, which can clearly be influenced by water flow and, in turn, can both help to define hydrogeological parameters and even influence flow directly (e.g. salinity gradients).

Each individual set can be broken up into individual subsets in a logical manner and each subset can, in turn, be subdivided further at an increased level of detail. To continue the example above, hydrogeology set i could be divided into a number of subsets – a logical example would be one for each geological formation present. The subsets, in turn, could be subdivided into different characteristic parameters – e.g. fracture distribution, fracture conductivity distribution, porosity, etc. This expansion to even further detail can be continued until the level of fundamental measurements or mechanistic models is reached. This inevitably becomes quite complicated at lower levels, but application of such a knowledge refining process in a bottom-up manner is already well established (e.g. within the geosynthesis process – see the example in section 3.1).

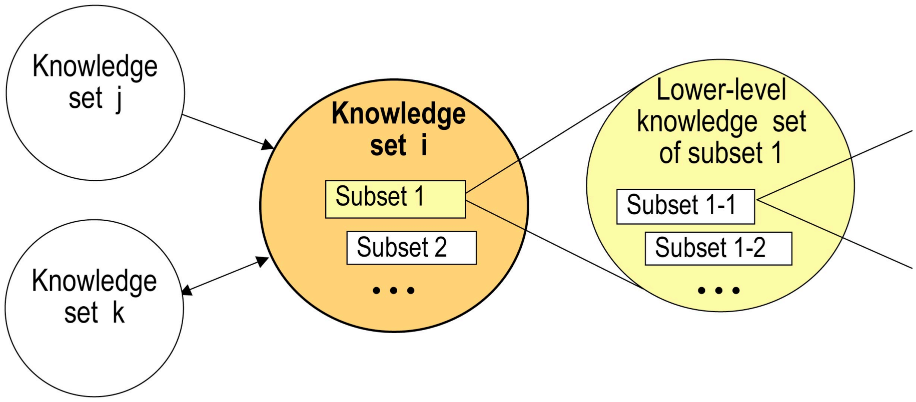


Figure 2-6: Principles involved in technical structuring of the knowledge base (see discussion in text).

In order to apply this approach, the considerations required to subdivide the safety case components outlined in section 2.2.4 into various levels of requirements on a project-specific basis is discussed (following the same numbering system).

(i) Purpose and context

The purpose and context of the safety case should be clearly and unambiguously defined, specifying the way in which it will be used for the specific step or decision point involved and hence the required robustness of the knowledge base used to support it as balanced against any residual uncertainties. As indicated in Figure 2-7, purpose and context can be subdivided into the level to which the system is specified and the regulatory requirements against which acceptability is measured. The first of these can be further divided as indicated, with further subsets containing knowledge to define:

- the waste inventory;
- the extent to which required attributes of the geological setting of the repository have been tested or confirmed;
- the extent to which the design basis for the repository system has been established;
- relevant safety, or other performance, goals or guidelines;
- defined political or programmatic boundary conditions (e.g. required QA, monitoring, …);
- etc.

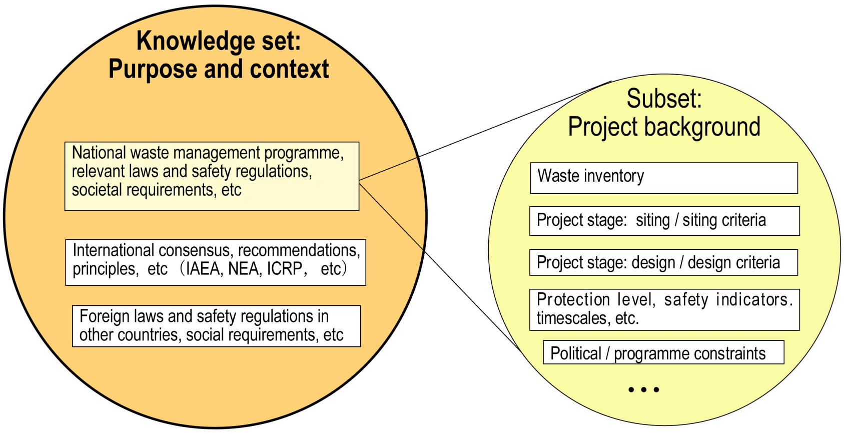


Figure 2-7: Structuring knowledge required to define the purpose and context of the safety case.

Regulatory requirements and specified procedures to determine compliance are clearly critical in defining the safety case aims but, at present, these are not yet defined in Japan. In the interim, however, a conditional case can be developed based on guidance issued by international organisations (e.g. IAEA, ICRP and NEA) and the existing situation in other national programmes which are more advanced in this area.

(ii) Safety strategy

The safety strategy is the high-level integrated approach adopted to ensure safe disposal, under the constraints established by the stated purpose and context (Figure 2-8). The three NEA subsets of management, siting/design and assessment strategies can then be further subdivided as indicated:

a) management strategy – further broken down into aspects associated with institutional management, ensuring that qualified manpower is available (with the required safety culture), ensuring that these institutions are flexible enough to cope with the stepwise evolving programme, installing required QM procedures (and applying them – also requiring a quality culture) and establishing the required R&D infrastructure;

b) siting and design strategy – including the basic philosophy of the repository concept (multibarrier system, robust engineered barrier system (EBS), etc.) and the approach used to tailor concepts to the sites arising from the chosen selection procedure;

c) assessment strategy – including the philosophy behind, and approaches to, the various steps of assessment: scenario development, consequence analysis, etc;

d) communication strategy - although not highlighted by the NEA, this may play a critical role in ensuring active commitment of key stakeholders and also in establishing credibility – which is a critical component of acceptability. This may be worth considering as a top-level subset, as active involvement of key stakeholders in the safety case development process is considered a particular challenge.

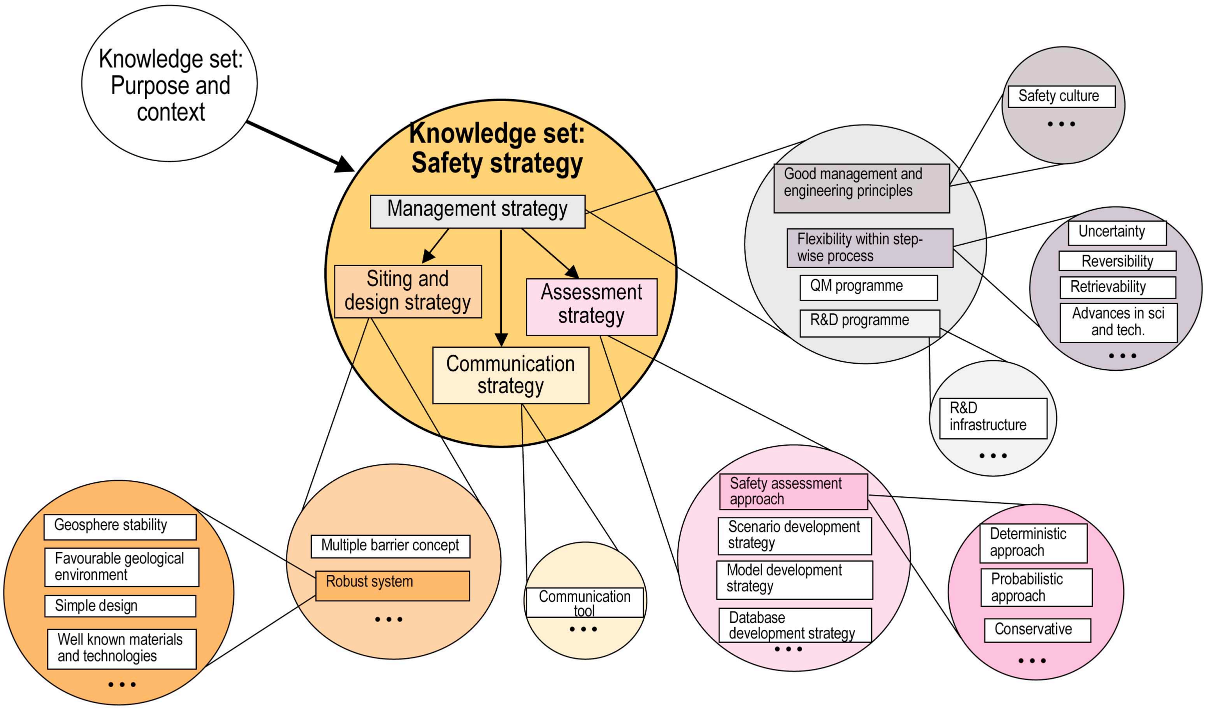


Figure 2-8: Structuring knowledge associated with the safety strategy.

(iii) Assessment basis

The assessment basis is a major component of the total knowledge base, including all information and analysis tools supporting the safety evaluation. This is broken down in Figure 2-9 under the subsets of system concept, scientific understanding and models/codes/databases used for quantitative analysis. Important subsets of knowledge identified in the further expansion of level of detail include:

a) system concept; the complete description of the disposal system, consisting of the geological setting and the concept for characterising it, along with the chosen repository design and the associated concept for construction, operation and closure. Both the site characteristics and the repository engineering can then be broken down in increasing levels of detail according to traditional technical disciplines;

b) scientific and technical information and understanding needed for assessment of system safety is here, as an example, broken down in terms of the subcomponents of the barrier system – near-field, geosphere and biosphere. These can, of course, be further broken down on a design- and site-specific basis;

c) as noted in section 2.1.2, quantitative assessment of post-closure safety will be strongly based on a modelling approach, so the assessment methods, models, computer codes and databases are key components of this basis. The structuring of the knowledge base illustrated includes the basic approach – comprising scenario development, scenario analysis, consequence analysis and uncertainty analysis. These can each be related to the methods and supporting models and data.

An important point arising from this figure – and by comparison with the previous Figure 2-8 – is that basic "bottom-level" knowledge may feed in to the derivation of several different upper-level knowledge sets. This is reasonable, as work in a particular area may be relevant to several different components of the safety case. The critical point is that the way in which the base knowledge is used to derive different higher knowledge sets will be specific to each. The critical point is that these derivation processes must be consistent and this is a key role of a formal knowledge management system.

As an example, the fundamental properties of the bentonite buffer would be an input for the three main knowledge subsets in Figure 2-9: repository design (within the system concept), scientific understanding (within the near-field phenomena) and models, codes and databases (under FEP lists and the databases for all of the analytical processes). It is clearly essential that all applications can be traced to an internally consistent buffer data set and that any changes in this set are reflected in all upper level applications of it. It can be noted that assuring such consistency has been a major issue in all past safety cases.

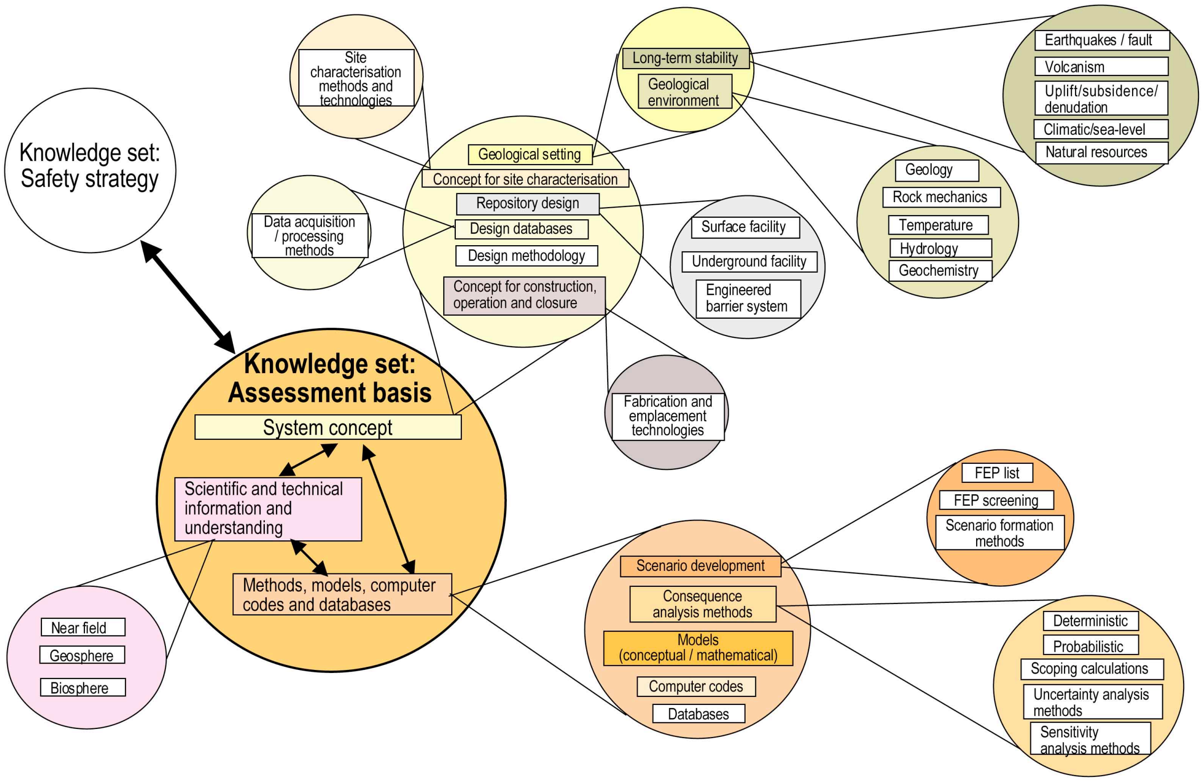


Figure 2-9: Structuring knowledge associated with the assessment basis.

(iv) Evidence, analyses and arguments

As previously emphasised, building a case that a concept is safe is strongly based on the results of the quantitative safety assessment. When carried out as defined in the assessment basis, the output of such analysis can be compared to safety or other performance requirements. As indicated in Figure 2-10, such quantitative analyses can produce not only both dose and risk assessments, but also other indicators of performance (e.g. extent of decay of toxicity within different barriers).

Such direct safety assessment needs, however, to be combined with other analyses (e.g. of complementary safety indicators) and more qualitative arguments to support the fundamental safety of geological disposal, the quality of the proposed disposal system and the quality of the analyses carried out. Each of these subsets can be broken down further as indicated and, again, there will be considerable overlap at the level of basic knowledge with that derived from Figures 2-8 and 2-9.

The evaluation of uncertainties plays an especially important role, as this involves not only an evaluation of any identified uncertainties on the claim of safety but also specification of how any key uncertainties can be reduced by planned site characterisation activities, further refinement of the design or improvement of the assessment process (approach / models / codes / databases). This will be a particular focus for review when a safety case is used to support a decision to move forward in a staged implementation process.

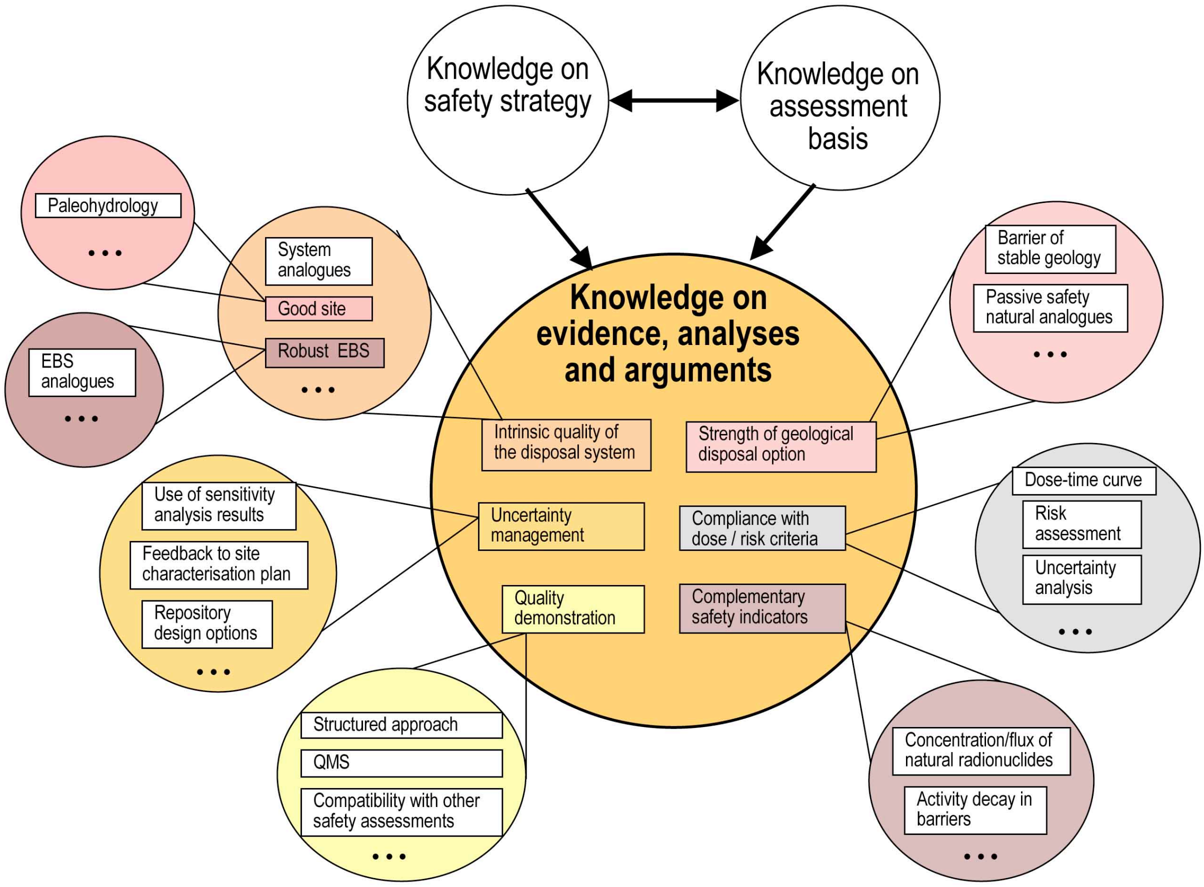


Figure 2-10: Structuring knowledge associated with evidence, analysis and arguments.

(v) Synthesis

The synthesis plays the key role of bringing together all information from the components of the safety case identified above and presenting them in a clear and logical manner which emphasises the key arguments leading to the final claim of safety. In effect, it involves a restructuring of the knowledge highlighted previously.

Here, there is a need to clearly distinguish between the objective knowledge within the knowledge base and the requirements and decisions which are dependent on the viewpoint of the user. Nevertheless, the process of organising the flow of information to optimise the rigour, transparency and effective documentation of decisions is itself a kind of knowledge. This is illustrated in Figure 2-11, where the very abstract process of developing a generic safety case as illustrated earlier in Figure 2-3 is transformed into a logical flow of evidence and arguments as suggested by the NEA (NEA, 2004). In fact, these could be specified as "requirements", to make the link to section 2.3.1 clearer.

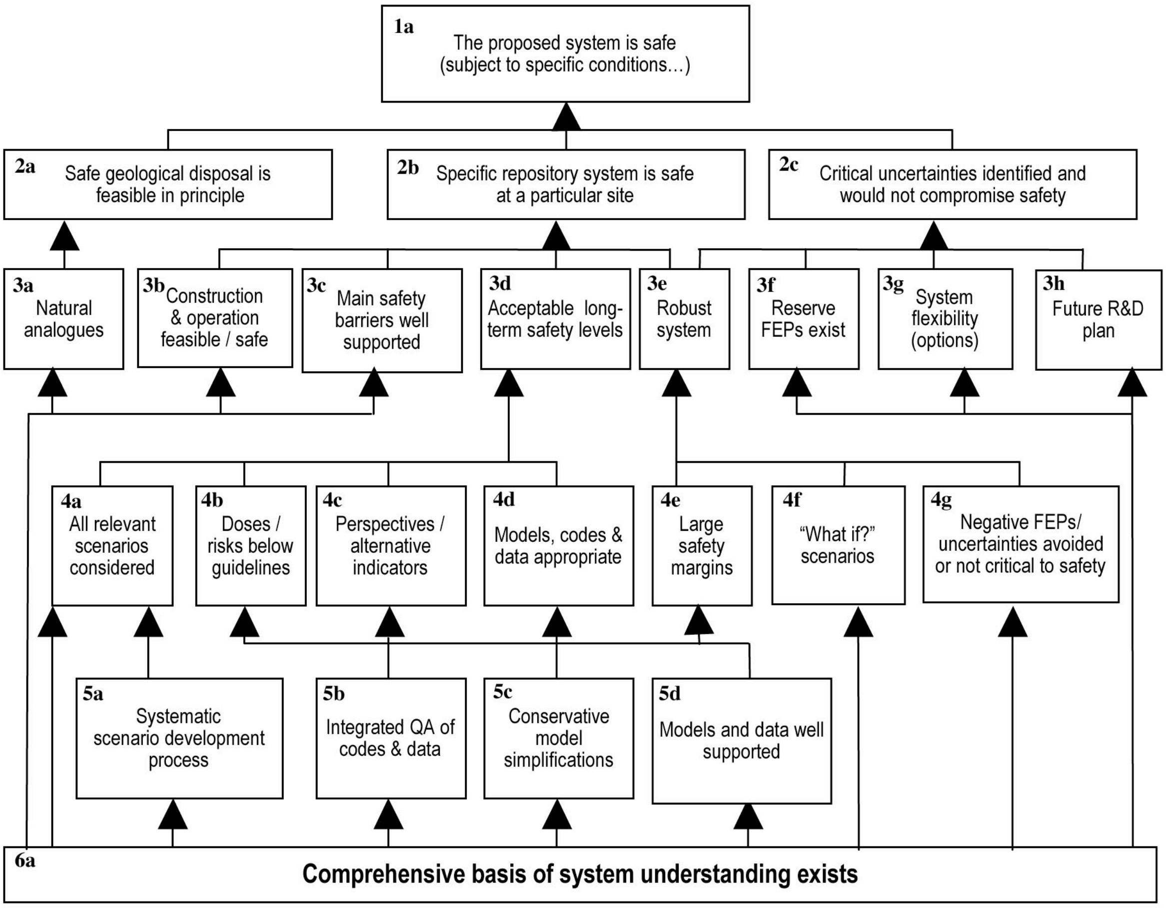


Figure 2-11: Hierarchy of statements and evidence and flow of knowledge (template) (based on an original concept by Paul Smith)

It is clear from Figure 2-11 that the underlying basis of system understanding is critical. The development of argumentation above this point is project- and stage-specific and will depend on whether the aim is developing a safety case (implementer) or reviewing it (regulator or other stakeholders).

For example, in Japan at the time of H12, the top-level statement in such a figure would be "Disposal of HLW in Japan would be feasible using existing technology and would pose no health risks post closure at a suitable location". The caveats included emphasise the generic stage of the programme at that point and the focus on long-term safety.

At the next level in the figure, for H12 the basic suitability of geological disposal does not necessarily need to be argued (although it is mentioned, with reference to other programmes) as this is an externally imposed system constraint (no other options were examined). The second-level claims would thus be:

- potentially suitable – i.e. stable - siting areas exist in Japan and can be identified / characterised using existing technology;
- the robust EBS design proposed would assure high levels of safety in a range of different potential siting environments;
- uncertainties have been identified, but do not call fundamental feasibility or safety into question.

The argumentation process can be continued further to consider increasingly detailed levels, becoming sequentially more project-specific. This will be illustrated for the next expected key safety case for HLW disposal in Japan, associated with the selection of PIAs, which will be mapped against the existing knowledge base as documented in the H12 / H17 reports in Chapter 3.

2.4 Summary

This Chapter has introduced the concept of a safety case and indicated its role in a stepwise implementation process. The implementation process utilises and generates vast quantities of information, data, experience, understanding, etc. – which we have defined broadly as "knowledge". The success of a project depends very much on the efficiency of structuring such knowledge. Using experience from complex, long-term projects in other industries, it is proposed to introduce a KMS to facilitate this process. Such a KMS has to be structured in a clear and logical manner, which is "user friendly". Again based on experience from other industries, this structuring can be provided by definition of the users' requirements, which are themselves ordered by the decision network inherent to the development of any project. If requirements are formalised within a RMS, the procedure can be optimised by directly interfacing the RMS with the KMS.

In the absence of a user RMS, the general process of structuring a knowledge base has been illustrated for the specific example of development of a safety case. This has shown that, although decisions and requirements are user-specific, the fundamental knowledge base needed to support them is much the same. The way in which base knowledge is transformed to the higher level knowledge sets is, in itself, a kind of knowledge and is a critical component of the KMS.

The evaluation of knowledge flows clearly illustrates that certain base knowledge can be used in different ways and ensuring consistency is also a key role of the KMS. The assurance of consistency and the structuring of the knowledge base help considerably in the synthesis of the safety case – which must be clear and acceptable to all stakeholders. The KMS must thus also extend to include active communication with stakeholders, and this point may be worth particular emphasis (see suggested extension of the NEA management strategy definition – Figure 2-8).

3 KNOWLEDGE BASE DEVELOPMENT

In order to give a more concrete example of knowledge base structuring and illustrate how this can be applied to the Japanese HLW project, the knowledge base established in the documentation of the H12 and H17 reports will be mapped against the requirements for the next safety case, which may have to be produced at the time of selection of PIAs. This will provide a clear indication of the present starting-point for the definition of formal requirements management systems by end users (e.g. Kitayama et al., 2005). The exercise will allow clear identification of important gaps in knowledge, which can be then prioritised by consideration of the staged implementation plan for HLW disposal in order to help define the future R&D programme. It must, however, be emphasised that the extent to which site-specific information is available at the stage of site selection may be very restricted and hence the distinction between such a safety case and the generic example provided by H12 would also be limited. For later stages – e.g. selection of Detailed Investigation Areas (DIAs) (NUMO, 2004d) – a much more rigorous, site-specific safety case would be needed.

3.1 Structuring the knowledge base

Figure 3-1 is a slightly modified version of the template provided by Figure 2-11, which specifically considers a synthesis for the type of conditional safety case which might be developed to support the decision to select (or accept) particular volunteer sites as PIAs.

When compared to the general Figure 2-11, a couple of significant differences are noticeable. Apart from the more specific level 1 claim, the most critical component of level 2 is the argument for geological stability. Unlike other aspects of the Japanese HLW programme, requirements for geological stability are enshrined in the Final Disposal Act and these have been interpreted by NUMO to produce openly published exclusion criteria (NUMO, 2002c). On the basis of such criteria, sites could be rejected directly as a result of literature data alone (e.g. presence of active faults, proximity to volcanoes, conflict with exploited natural resources).

The other significant difference is the subdivision of system understanding (base level 6) into site-specific and generic components. This is to facilitate discriminating between sites as, in principle, a safety case would need to be made for each potential PIA and such subdivision allows comparison to be focused on site-specific aspects.

At intermediate levels 2-5, the other arguments are more conventional, associated with a practical and safe repository and absence of critical uncertainties.

It is now possible to work through this argumentation scheme, examining what knowledge input would be required to support these statements (or requirements). This will be done sequentially, in a top-down manner, emphasising the top-level datasets needed. In some cases, indications of how these can be broken down in more detail can be illustrated (e.g. with reference to the safety case component knowledge sets described in section 2.3.2). The extent to which these specific knowledge requirements have already been covered can be assessed by mapping them to the H12 / H17 R&D reports. The linking of requirements to such knowledge documentation is a convenient way of preparing the ground for the implementation of a formal KMS if a documentation-based, relational database approach is adopted (see section 3.3). In the following discussion, numbered in sequence from the top as shown in Figure 3-1, the available knowledge base relevant to H12 and H17 is referred to on a volume basis as summarised in Tables 3-1~3-21, using the following symbols:

- H12
  - OR: Overview Report (JNC, 2000a)
  - V12-1: Supporting Report 1 (JNC, 2000b)
  - V12-2: Supporting Report 2 (JNC, 2000c)
  - V12-3: Supporting Report 3 (JNC, 2000d)
- H17
  - V17-1: Supporting Report 1 (JNC, 2005b)
  - V17-2: Supporting Report 2 (JNC, 2005c)
  - V17-3: Supporting Report 3 (JNC, 2005d)

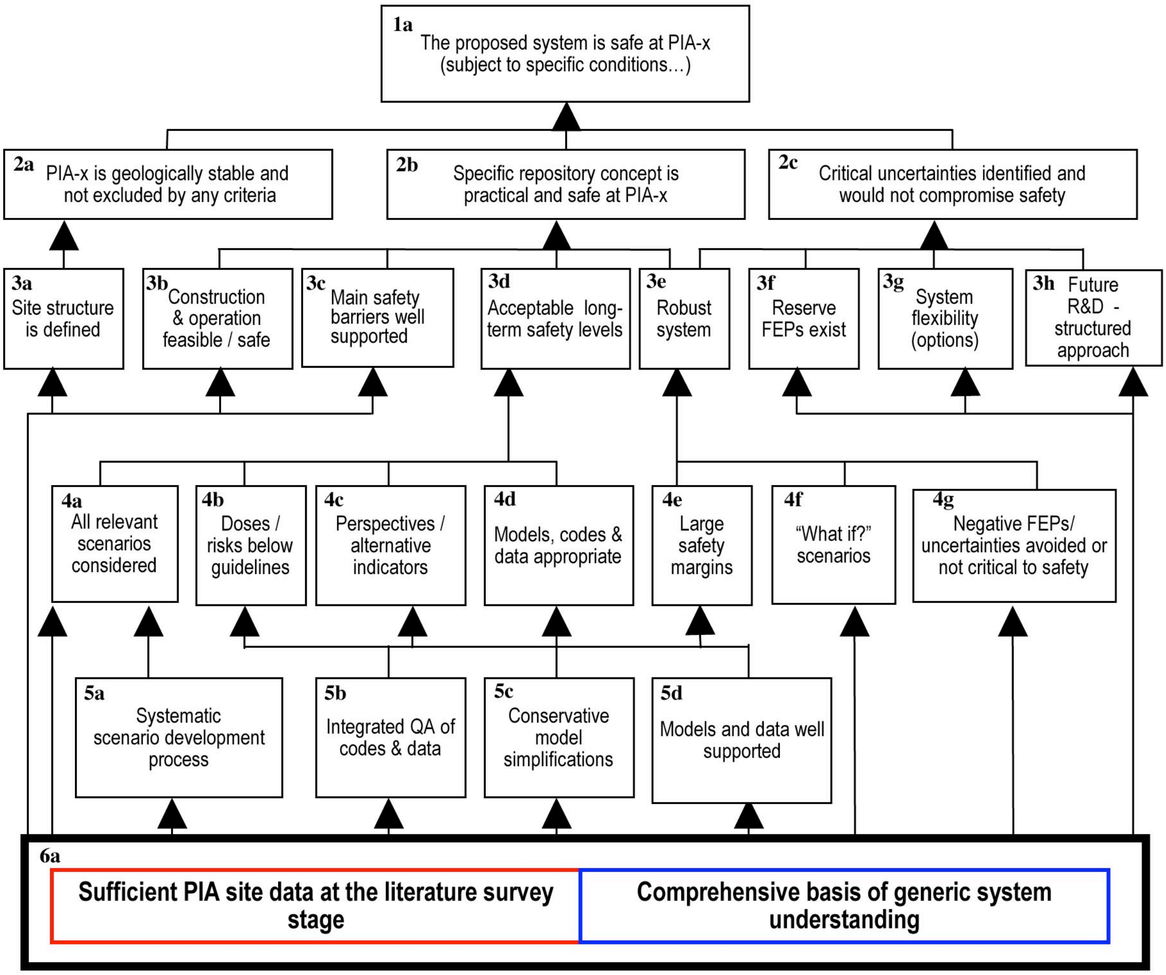


Figure 3-1: Arguments and information flow for a safety case to support selection of a specific PIA ("PIA-x"). The hierarchy can be considered as requirements, which need to be supported by knowledge sets derived from fundamental, basis knowledge (level 6) which is subdivided pragmatically here into that which is generic and that which is specific to the particular site. In discussing levels, these requirements (and their supporting upper-level knowledge sets) are numbered from the top.

(1) Level 1

In terms of the level 1 claim of system safety, the purpose and context (Figure 2-7) need to be well defined. For this case, it would be clearly documented that:

- The aim is to eliminate PIAs which are clearly technically unsuitable as potential hosts for a HLW repository constructed and assessed on the basis of existing knowledge (or reasonable extrapolations thereof);
- The context and boundary conditions are established by law;
- The sites considered are all volunteers;
- Site characterisation is limited at this stage to literature surveys; all assumed characteristics are thus conditional on confirmation by field studies;
- Model system concepts are developed based on such assumed characteristics, but these are provisional only and would be modified in the light of better site understanding;
- Practicality of the construction and operation phases in terms of quality / time / budget constraints is not evaluated in detail and the assessment of safety during these phases is carried out only at a very basic level;
- Post-closure safety assessment is based on available site and concept assumptions and their associated caveats.

It is thus clear that the safety case will tend to be rather preliminary, associated with many conditional statements and caveats. In particular, the regulatory guidelines and the requirements for compliance may not yet be established at this time (NSC, 2000), which places a fundamental constraint on the rigour of any derived safety case. Nevertheless, the level and significance of uncertainties will play a clear role and these are impossible to predict completely in advance – being defined by the complexity of the siting environment volunteered and the extent and quality of available literature.

Despite the limitations of the safety message, the exercise of developing a safety case at this stage is valuable as an illustration of an open commitment to safety (see section 2.2.4 (1)), which contributes to acceptance, but also serves to identify site-specific issues - which may be important in the future for more rigorous safety cases.

Apart from such specification of constraints on the safety case, this claim would be supported by direct input from the next level of argumentation.

(2) Level 2

Three arguments are presented at this level, of which the first – the claim that the PIA is geologically stable – is the most critical and associated with clearly specified acceptance criteria.

2a) Geological stability: published exclusion maps (NUMO, 2002c, 2004d) could allow some sites to be precluded from further consideration in a rather clear manner but, if this was the case, it is unlikely that the effort would be taken to prepare a safety case. Even if not clearly excluded, however, literature data may indicate suggestions of characteristics which could call the stability of the site into question (e.g. Figure 2-9). To evaluate the significance of such observations, national and regional databases of active faults, volcanism, uplift / erosion and natural resources will be needed. These are already well established and are maintained at the state of the art by incorporating new knowledge as it arises (Table 3-1). It may also be necessary to emphasise that the conceptual understanding of the complex tectonic setting of Japan is being actively advanced to reduce associated uncertainties – something which has already been initiated by NUMO (e.g. Apted et al., 2004).

Table 3-1: Knowledge supporting 2a) site geological stability.

Knowledge	H12	H17
Active faults / earthquakes	OR / V12-1	V17-1
Volcanism	OR / V12-1	V17-1 / V17-3
Uplift / erosion	OR / V12-1	V17-1
Natural resources	OR / V12-1	V17-1
Exclusion maps	NUMO (2002c)	
Tectonic understanding	e.g. Apted et al. （2004）	
Site synthesis	not yet available	

2b) Repository concept is safe and practical: this claim will be supported by the knowledge base in Figure 2-9 and, to the extent possible, by analyses made with site-specific data. As such data may well be very limited, particular reference may be made to the knowledge base supporting the H12 claim of the fundamental feasibility of HLW disposal in Japan, combined with an assessment of how consistent the site is (as defined by the site synthesis) with the geological properties assumed at that time (Table 3-2). This could be extended by comparison with relevant international repository projects.

The claim will clearly be associated with uncertainties, and hence the concept for tailoring the concept to the site would also be introduced at this stage.

Table 3-2: Knowledge supporting 2b) repository concept safety and practicality.

Knowledge	H12	H17
Fundamental feasibility in Japan	OR / V12-2 / V12-3	
International examples	OR	
International update	not yet available	
Concept of tailoring	NUMO (2004c)	
Site-specific synthesis	not yet available	

2c) Uncertainties would not compromise safety: argumentation here would focus on the fundamental robustness of the entire system to uncertainties, with particular reference to the H12 concept with emphasis on a robust EBS, which has few requirements on the geosphere apart from sufficient stability to ensure EBS longevity. Relevant knowledge is classified in Figures 2-8, 2-9 and 2-10. Again this would be confirmed by comparison of H12 geosphere assumptions to the site-specific synthesis for the potential PIA (Table 3-3). Argumentation could be strengthened by NUMO's work, to show the wider range of environments which could prove to be acceptable by considering alternative design options.

Table 3-3: Knowledge supporting 2c) concept robustness.

Knowledge	H12	H17
Focus on robust EBS	OR	
Designing for robustness	NUMO (2004c)	
Site-specific synthesis	not yet available	

(3) Level 3

This level brings together the results of assessments. As such, many of the issues are similar to those involved in combining evidence, analysis and arguments (Figure 2-10) in different topical areas.

3a) Site structural model: this will predominantly be a synthesis of the information derived from the literature survey. This forms a knowledge base as classified in Figure 2-9. The status of knowledge supporting the site structural model is summarised in Table 3-4. Confidence in the procedures involved can be argued on the basis of past (and ongoing) work – particularly at the Mizunami and Horonobe URLs. The site model may also be limited in terms of completeness. In this case, extrapolations from similar sites in the national GIS database might be used.

Table 3-4: Knowledge supporting 3a) the site structural model.

Knowledge	H12	H17
Methodology & experience: Generic URL sites	OR / V12-1	V17-1 V17-1
Site-specific database	not yet available	
Complementary national database	GIS (e.g. Committee for Standardization of Spatial Data, 1999)	

3b) Construction and operation: basic feasibility of construction would be based on the past generic studies, again with comparison of site data to the assumed H12 conditions to justify applicability. This knowledge is classified in Figure 2-9 and the status is summarised in Table 3-5. Very simple illustration of operational procedures in H12 might be used for illustrative purposes, but are certainly not defendable on a site-specific basis. Argumentation for safety may therefore focus on identified work areas which will clarify uncertainties – some of which have already been initiated (e.g. RWMC, 2003). These feature in the R&D programme.

Table 3-5: Knowledge supporting 3b) the feasibility / safety of construction and operation.

Knowledge	H12	H17
Fundamental feasibility	OR / V12-2	
Construction experience (including URLs)		V17-1
Site-specific database	not yet available	
Construction safety analysis	not yet available	
Operational safety analysis	not yet available	
EBS emplacement practicality	e.g. RWMC (2003), R&D programme	

3c) Main safety barriers: as the barrier focus will inevitably concentrate on the EBS, this argument will be based mainly on the very extensive knowledge base in H12 (Figure 3-2), complemented by H17 documentation of work to maintain knowledge at the state of the art and clarify some previously identified open questions (see Figure 2-10). Table 3-6 summarises knowledge supporting the main safety barriers.

Such understanding is complemented by natural analogue studies, which need to be assessed for their relevance to the site involved. Also, site-specific engineering materials needed (e.g. liners, grouts, etc.) may have to be discussed in terms of any concerns they might raise with regard to the critical barrier functions.

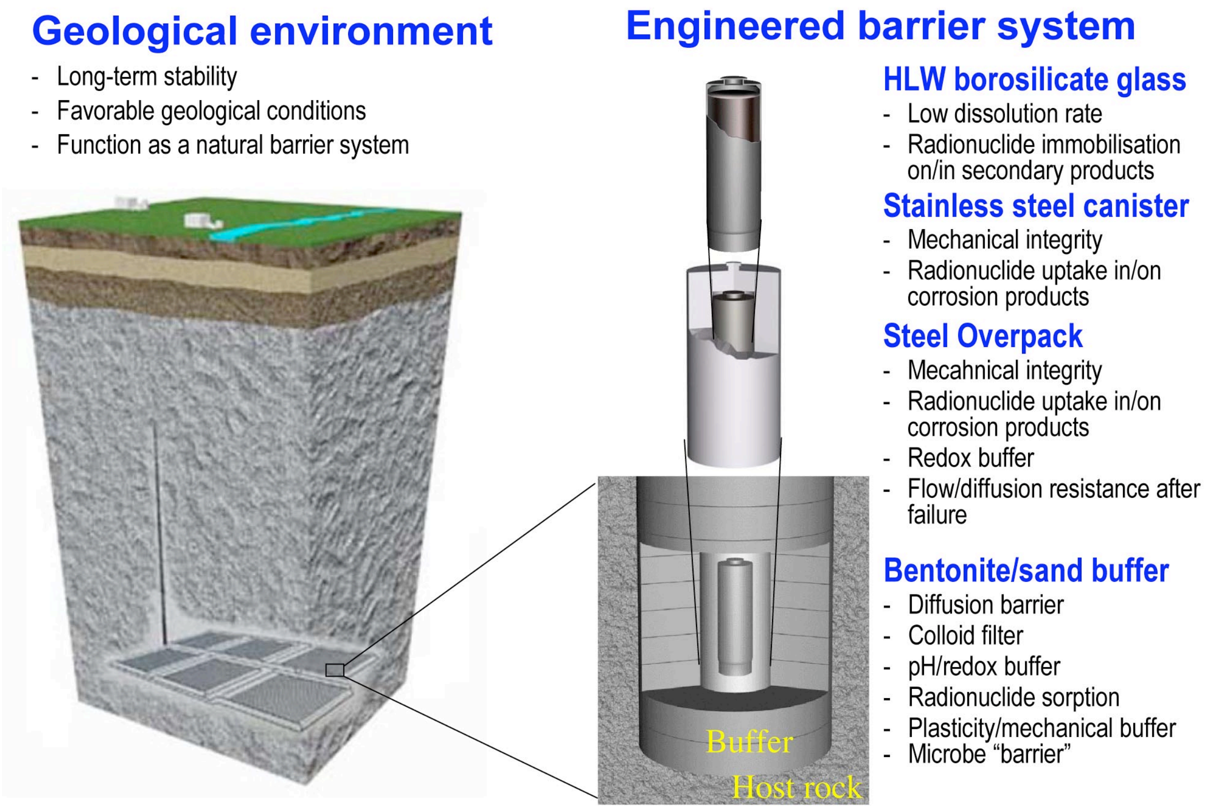


Figure 3-2: H12 safety barrier system: components and potential roles (NB: not all of these barrier roles were analysed in the H12 study).

Table 3-6: Knowledge supporting 3c) the performance of the main safety barriers.

Knowledge	H12	H17
EBS properties	OR / V12-2	V17-2
EBS performance	OR / V12-2 / V12-3	V17-2 / V17-3
Geological barrier performance	OR / V12-1 / V12-3	V17-1 / V17-3
Analogues	OR / V12-1 / V12-2 / V12-3	V17-1 / V17-2 / V17-3
Influence of additional materials	V17-2, R&D programme	
Site-specific database	Not yet available	

3d) Acceptable long-term safety: this argument will be based predominantly on the results of a site-specific analysis (see Figures 2-9 and 2-10), which cannot be predicted in advance. The results would, however, be compared to those from H12 and discussed in terms of consistency. A comparison with specific international safety assessments might also be included if sites had any specific similarities.

Here, the strong interaction between this topic and the arguments 3e, 3f and 4c should be noted (specific to the particular case of tailoring designs to volunteer sites).

There are strategic benefits to be gained by mobilising specific reserve FEPs (3f) – especially in the case of a potentially suitable but poorly characterised site. Even if these cannot be fully quantified, they can be introduced into the main assessment and further clarification established as a component of the R&D plan. This would be a decision by the implementer, based on an overview of the strength of different components of the knowledge base and an assessment of the concerns of key stakeholders (Table 3-7).

Table 3-7: Knowledge demonstrating 3d) long-term safety.

Knowledge	H12	H17
H12 PA	OR / V12-3	
International overview	OR / V12-3	
Site-specific analysis	not yet available	
International update	not yet available	
Reserve FEP mobilisation options	R&D programme	

3e) System robustness: the claims for system robustness are also strongly based on the underlying analysis – both within the safety assessment and in the evaluation of uncertainties / "what if?" scenarios (Figure 2-10). As noted previously, the balance of the arguments supporting robustness / reserve FEPs could, potentially, be changed if desired.

Nevertheless, the basis of robustness arguments will focus on the performance of the EBS in a deep geological environment. This is based on use of well known materials, extensive databases and analogues – as documented in H12 and confirmed by some H17 backup work (e.g. Figure 3-3). Some open questions identified at that time may need further discussion (e.g. gas, organics, colloids, microbes) – although some relevant supporting information may already be available.

The properties of the site may, however, need to be assessed to check if any issues influencing EBS robustness arise. There are clear links here to the concerns in 3c, especially in the case where the site requires additional engineering measures whose possible interaction with the main EBS needs to be assessed (e.g. use of concrete-based materials may decrease robustness, Metcalfe and Walker, 2004). Table 3-8 summarises the knowledge supporting system robustness.

Table 3-8: Knowledge supporting 3e) system robustness.

Knowledge	H12	H17
EBS robustness (concept)	OR / V12-3	
Extensive databases	V12-2 / V12-3	V17-2 / V17-3
Open questions (partially)	OR / V12-1 / V12-2 / V12-3	V17-1 / V17-2 / V17-3
Site-specific safety assessment	not yet available	
Site-specific sensitivity analysis	not yet available	
Further clarification of open questions	Metcalf & Walker (2004), R&D programme	

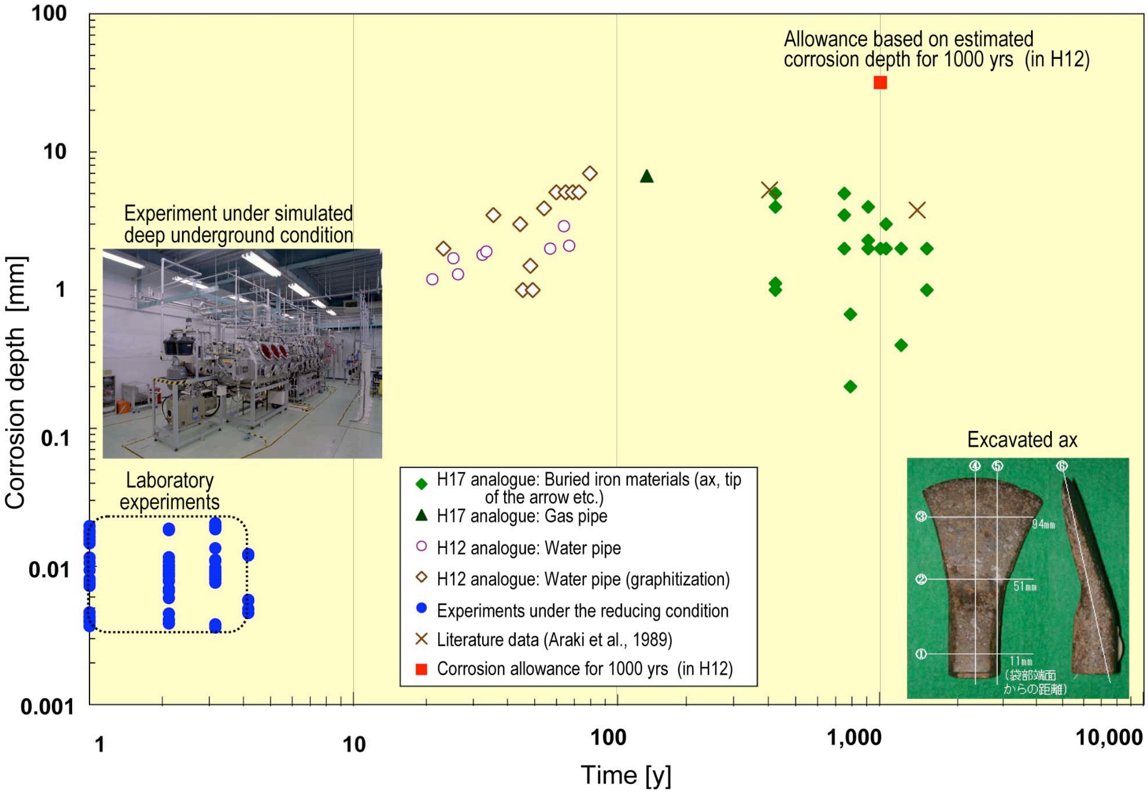


Figure 3-3: Robustness of the system: integration of arguments and data from multiple sources for a well known material (iron / steel). Shown here is the measured corrosion depth for different time periods (red: design value, blue: laboratory experimental measurements, white: analogue studies in H12, green: analogue studies in H17).

3f) Reserve FEPs: FEPs within the geological barrier (see Figure 2-9) would be impossible to specify in detail until the site has been characterised and hence near-field analysis will be the main input to this claim. As noted before, however, there is a strategic choice associated with defining particular FEPs as "reserve" if there is any prospect of mobilising them – either directly or in the future. Within the EBS, in particular, there is considerable potential for strengthening the safety assessment (e.g. more realistically distributed canister failure, co-precipitation, etc.) if this were required – although this would need to be balanced by an appropriate R&D effort.

The starting list of reserve FEPs can be derived from H12, although applicability would, in a few cases, need to be checked against site-specific characteristics. Some effort to examine the significance of reserve FEPs (e.g. co-precipitation) is included in H17 (Table 3-9).

Table 3-9: Knowledge supporting 3f) the selection and analysis of reserve FEPs.

Knowledge	H12	H17
Starting FEP list	OR / V12-3	
Assessment of the value of mobilising reserve FEPs	V17-3, R&D programme	
Site-specific FEPs	not yet available	

3g) System flexibility; the H12 study has already illustrated a wide range of different options in terms of materials, design and layout which allow a flexible response to encountered site conditions (relevant to Figures 2-9 and 2-10). This has been taken further by NUMO, who have widened the range of design options based on the fundamental H12 engineered barriers and examined processes for tailoring designs to particular siting environments.

To date, however, the limits on the applicability of this concept have not yet been rigorously established. This would, however, become critical only for a site that was near the limits of applicability (e.g. very small area, very deep or shallow potential host rock, etc.) (Table 3-10).

Table 3-10: Knowledge supporting 3g) system flexibility.

Knowledge	H12	H17
H12 options	OR / V12-2	H17-2
Alternative designs	NUMO (2004c)	
Limits of applicability of options	R&D programme	
Site-specific boundary conditions	not yet available	

3h) Future R&D; credibility of this programme to identify and clarify open issues will be facilitated by the structured implementation programme (NUMO, with associated RMS) and the introduction of a formal KMS (JNC – JAEA). This should, for example, flag all issues identified in this section and allow them to be addressed efficiently in terms of their significance for safety and their relevance at different programme stages (Figure 2-8).

(4) Level 4

At this level, the assessment results supporting level 3 are derived from assessment models and databases. The procedures and toolbox used in H12 received an international review (NEA, 1999c) and could, at that time, be considered as being state of the art. The key issues for supporting the safety case at this level would thus focus on whether technical developments since H12 or the characteristics of the particular sites call any of the safety-relevant knowledge (data, understanding, models, interpretation, etc.) into question – or, indeed, have they been strengthened in the interim. The knowledge related to arguments at level 4 is mainly linked to Figures 2-9 and 2-10.

4a) All relevant scenarios considered: emphasis on the site characteristics to determine whether any specific scenario could cause disruption of the robust EBS, with argumentation based on the underlying scenario development process and the site characterisation data (particularly the site evolution model). Support can be derived from experience in this process gained during H12 and analysing the URL sites. The site evolution model may require the literature data to be complemented by regional or national information.

Table 3-11: Knowledge supporting 4a) relevant scenarios.

Knowledge	H12	H17
Methodology & experience:	OR / V12-3	V17-3
Complementary regional / national database	GIS (e.g. Committee for Standardization of Spatial Data, 1999)	
Site evolution model	not yet available	

4b) Doses / risks below guidelines: as it is possible that guidelines will not yet have been established at this time, the discussion of other national programmes would be relevant. This may, however, need to be updated. The values of dose / risk compared with these measures derive from the lower level, site-specific analysis, which might be put in context by comparison with H12 results (Table 3-12).

Table 3-12: Knowledge supporting 4b) risks below guidelines.

Knowledge	H12	H17
National regulations overview	OR / V12-3	
H12 dose / risk results	OR / V12-3	
Regulatory guidelines for HLW	not yet available	

4c) Perspectives and alternative indicators: again based on the site-specific analysis, but would reference H12 work in terms of providing background (Table 3-13). Comparisons with the results from other relevant assessments may need to be updated. Since H12, further work has been carried out to evaluate fluxes in the biosphere (Figure 3-4), which can be applied to relevant elements – e.g. natural uranium – for comparison to repository releases in the far future.

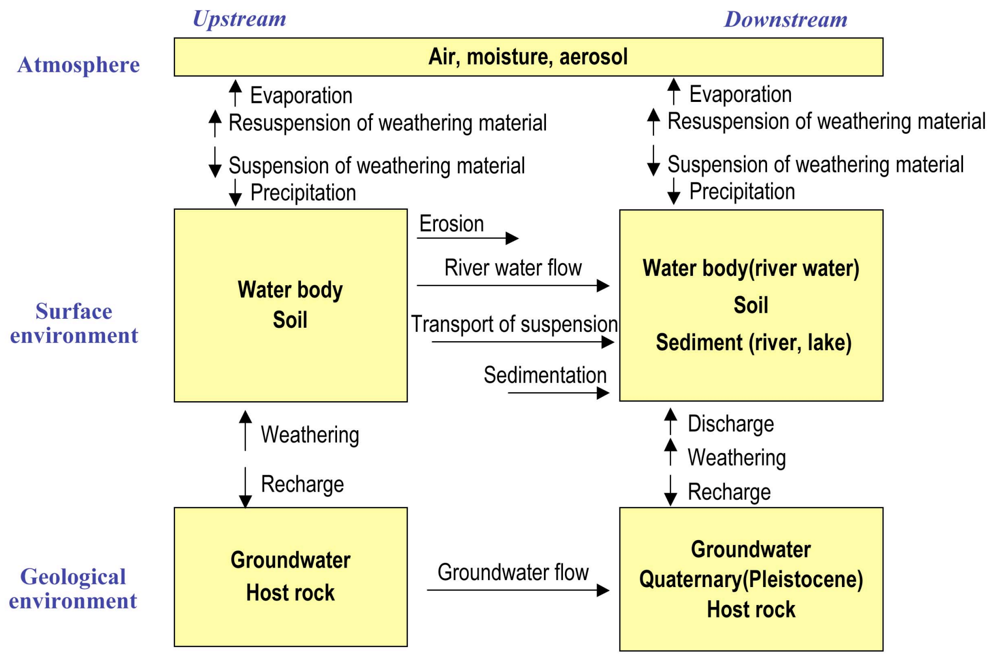


Figure 3-4: Mass transport processes to be considered when developing a method for evaluating fluxes of naturally occurring materials. Boxes show compartments which contain these materials, while arrows denote processes which result in transportation between compartments (JNC, 2005d).

Table 3-13: Knowledge supporting 4c) perspectives and alternative indicators.

Knowledge	H12	H17
Perspectives background	OR / V12-3:	V17-3
Safety assessment update	not yet available	

4d) Models, codes and data appropriate: it is expected that the analysis would be carried out with effectively the same model chain as H12 (Figure 3-5), which can be considered to be peer-reviewed. Argumentation here would focus on any generic developments in this chain, updates in the database and site-specific models introduced. The status of knowledge supporting the models, codes and databases is summarised in Table 3-14.

Table 3-14: Knowledge supporting 4d) models, codes and databases.

Knowledge	H12	H17
Model chain	OR / V12-3	V17-3
Site-specific models	not yet available	
Model chain update	not yet available	

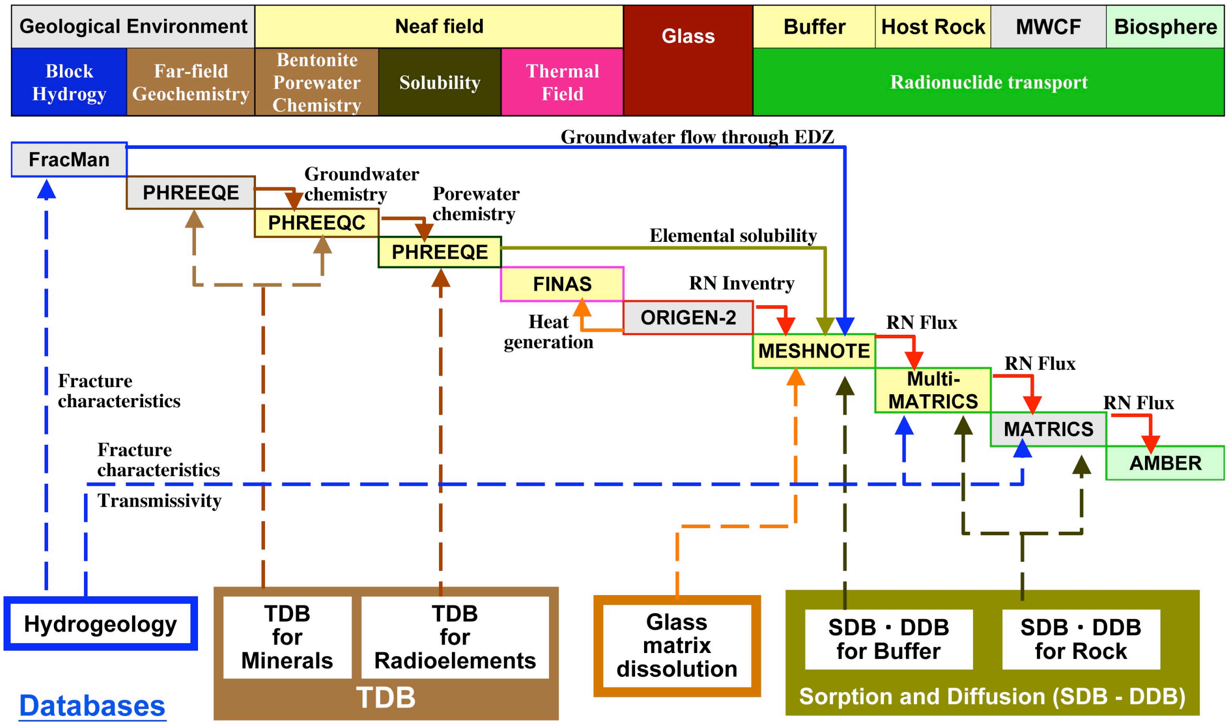


Figure 3-5: Model chain used in the H12 safety assessment and associated flow of information (JNC, 2000a).

4e) Large safety margins: as discussed for 3d, 3e and 3f above, the extent of such margins depend on the assessment strategy, in addition to the results of the underlying, site-specific calculations. In the event of great uncertainty in the site, the safety margins argument could focus on the conservatism involved in the design and assessment of the individual engineered barriers, based on a detailed understanding of their properties (Table 3-15).

Although many site factors contribute to safety, two critical attributes influencing doses are the transit time to the biosphere and the dilution factor. If either of these can be implied to be as good as (or better than) H12, arguments for safety margins could be extended to the geosphere.

Table 3-15: Knowledge supporting 4e) safety margins.

Knowledge	H12	H17
General EBS margins	OR	
Glass	V12-3	V17-3
Overpack	V12-2 / V12-3	V17-2
Bentonite	V12-2 / V12-3	V17-2 / V17-3
Site-specific safety margins	not yet available	

4f) "What if?" scenarios: these are highly stylised representations and, in many cases, would be little influenced by the site and hence could be based on H12 cases (e.g. no geosphere, although note that this depends on the assumed dilution factor).

The major perturbation scenarios (e.g. volcanism, faulting, uplift / erosion, human intrusion) are also effectively "what if?" scenarios (although human intrusion may need special consideration) – if discussed at all. Updated system understanding since H12 can also be introduced (Figure 3-6) and, if justified, scenarios modified to make them more site-specific (e.g. with regard to topography, setting – this could be especially relevant for a coastal or island site) (Table 3-16).

Table 3-16: Knowledge supporting 4f) what if? scenarios.

Knowledge	H12	H17
Basic what if? scenarios	OR / V12-3	
Advances in understanding Volcanism Faulting Uplift / erosion		 V17-1 / V17-3 V17-1 V17-1
Site-specific what ifs	not yet available	

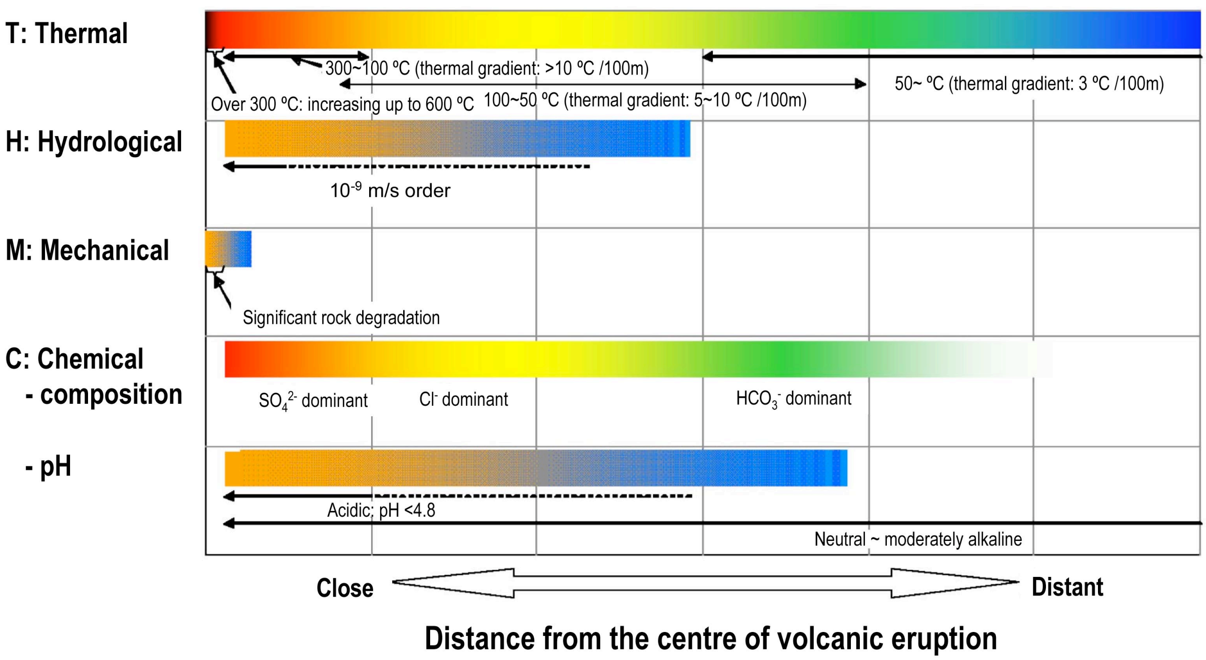


Figure 3-6: Example of integration of knowledge to support what if? scenarios relating to volcanic activity. Extent of thermal, hydrological, mechanical and chemical perturbations as a function of distance from the centre of a volcano (JNC, 2005d).

4g) Negative FEPs: again treatment for the EBS can be based on H12, although work done since then to avoid such FEPs by design or to demonstrate that their significance for safety is minor should be included. A site-specific analysis would be needed to identify any novel issues which may be of significance (e.g. geo-gas, very high salinities) – which would either be discussed directly or lead to proposals for future R&D (Table 3-17).

Table 3-17: Knowledge supporting 4g) analysis of negative FEPs.

Knowledge	H12	H17
EBS negative FEP analysis	OR / V12-3	
Understanding negative FEPs Colloids (Figure 3-7) Organics Microbes Gas High pH plume		 V17-3 V17-3 V17-3 V17-2 V17-2 / V17-3
Site-specific negative FEPs	not yet available	
Work to clarify site-specific FEPs	R&D programme	

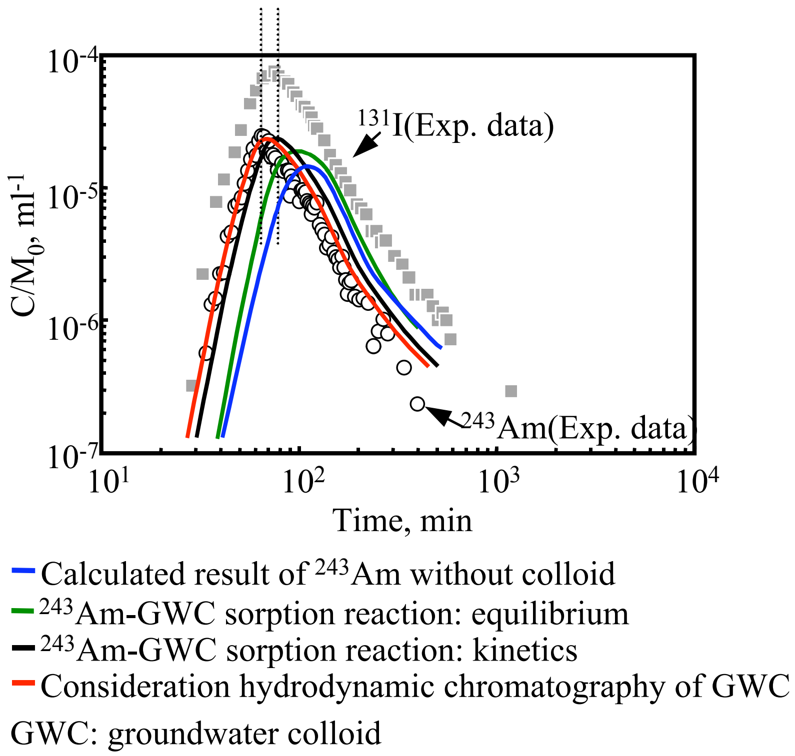


Figure 3-7: Improved understanding of colloid transport of radionuclides: an in-situ experiment on colloid and radionuclide retardation (CRR experiment) has been conducted at the Grimsel Test Site in Switzerland to investigate possible radionuclide migration enhancement by colloids. Shown here is a comparison of breakthrough curves for Am in the CRR experiment with the COLFRAC calculated results (Kurosawa et al., 2005).

(5) Level 5

This level involves the development of the models and their associated databases. These can be classified into the knowledge shown in Figure 2-9.

5a) Systematic scenario development: this procedure is effectively site-independent and was established and reviewed for H12. It would probably form the basis of a PIA analysis, with an associated update on international progress in this area (in particular, comprehensive FEP lists, e.g. NEA, 2000; Mazurek et al., 2003) (Table 3-18). However, it should be noted that NUMO has indicated an intention to move towards more dynamic scenario descriptions (NUMO 2004c), which would need significant new development of approaches in the future.

Table 3-18: Knowledge supporting 5a) scenario development.

Knowledge	H12	H17
Scenario development procedure	OR / V12-3	V17-3
Procedures / FEP list update	not yet available	
Next-generation dynamic scenarios	R&D programme	

5b) Integrated QA: this is an essential requirement, which should follow on from the QM system specifications developed by NUMO. In the interim, technical quality arguments can focus on internal and external review processes (Table 3-19).

Table 3-19: Knowledge supporting 5b) QA.

Knowledge	H12	H17
Past QA measures	OR / V12-2 / V12-3	V17-3
NUMO QM guidelines	not yet available	

5c) Model simplifications: this is a critical area for arguing that the basic model chain is appropriate to the system studied and that the transformation from basic understanding to the models (and parameters) used in the safety assessment is clear and defendable. The basis of this for the EBS and geosphere is documented in H12 and has been extended in work since then.

For the far-field, basic processes used to derive solute transport models can be argued based on H12. However, a clear process needs to be shown for simplifying field observations to derive the safety assessment models and databases. This "geosynthesis" (Figure 3-8) has been developed and demonstrated for URL sites and can be used to support arguments for the volunteer site, even in the event of incomplete characterisation data.

Even though the biosphere is acknowledged to be an idealised representation aimed only at illustrating the relevance of radionuclide releases (documented in H12), it is important for confidence-building that this should represent the real site to the greatest extent possible (NB the principles involved here are understood by even non-technical audiences). A future action, therefore, would be tailoring general biosphere models to the present environment of the site considered.

The relevant knowledge supporting arguments for model simplifications is summarised in Table 3-20.

Table 3-20: Knowledge supporting 5c) model simplifications.

Knowledge	H12	H17
Basis for EBS SA models	OR / V12-2 / V12-3	
Further system understanding Source term Canister failure FF transport		 V17-3 V17-2 V17-3
Basis for far-field models	OR / V12-1 / V12-3	V17-1 / V17-3
Demonstration of geosynthesis approach		V17-1
Biosphere justification	OR / V12-3	V17-3
Site-specific geosynthesis	not yet available	
Site-specific biosphere	R&D programme	

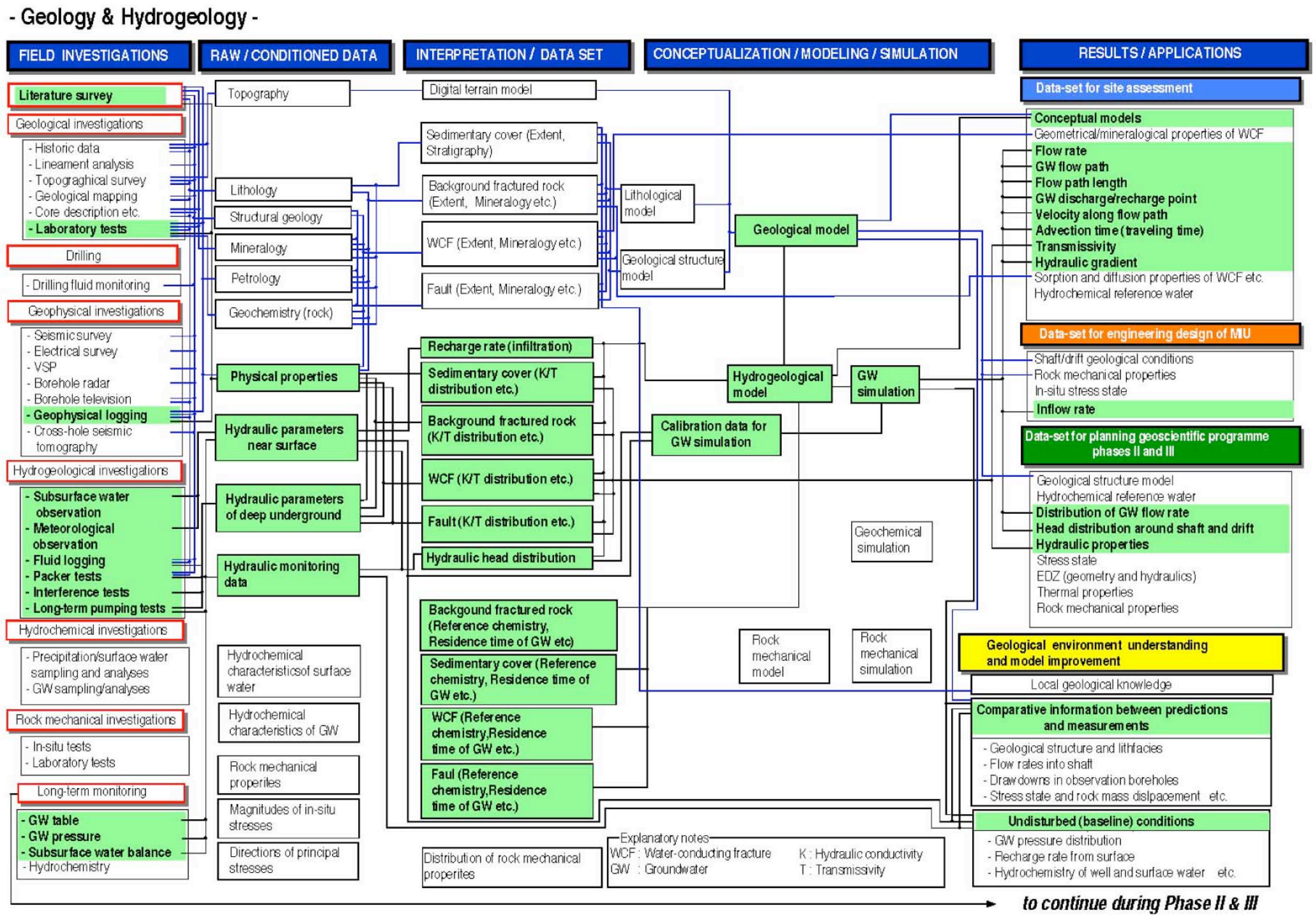
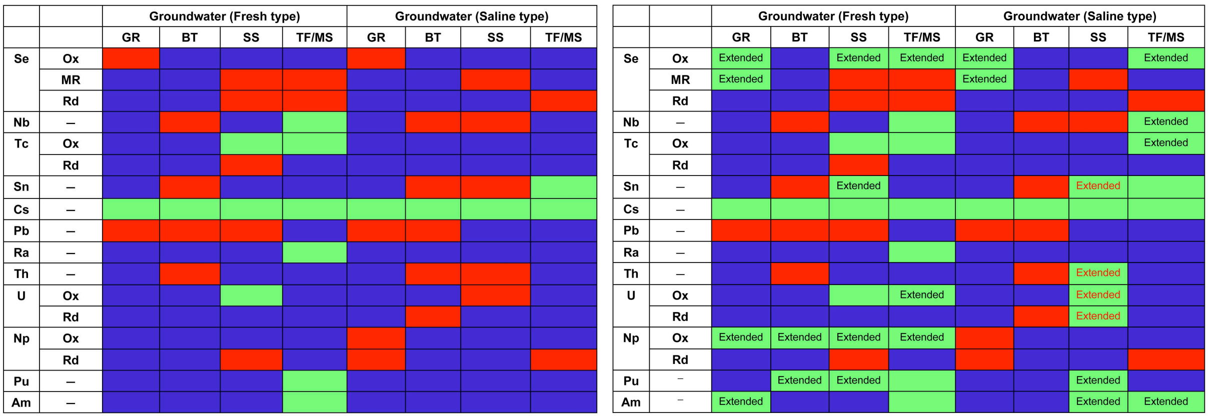


Figure 3-8: **Example of a systematic framework for deriving simple models and data from a complex system: the "geosynthesis" of geology and all other associated earth science aspects (after Saegusa et al. (2003)).**

5d) Models and data well supported: the basic models and data for H12 were fully documented. Very important here, however, is to show that these are maintained at the state of the art and represent latest developments. Ongoing development of models and databases is evident from the JNC R&D programme, with emphasis on generic or "semi-generic" data (Figure 3-9). This needs to be extended to consider the models and data for a specific site – especially if it falls outside the range of characteristics considered in H12 (Table 3-21).



Note) Ox: oxidising condition, Rd: reducing condition, MR: moderate reducing condition.
GR: granite, BT: basalt, SS: sandstone, TF/MS: tuff/mudstone.
Green box: extensive data, *Blue box*: some data, *Red box*: very limited or no data.
Extended (black script): no alkaline conditions included.
Extended (red script): including a range of alkaline conditions.

(a) at the time of H12 (b) after H12

Figure 3-9: Development of the JNC'sorption database (SDB) to extend the coverage of safety-relevant elements in potential siting environments (JNC, 2005d).

Table 3-21: Knowledge supporting 5d) justification of models and data.

Knowledge	H12	H17
Support of basic models & data	OR / V12-2 / V12-3	
Updating of model support		V17-1
Updating of databases		V17-2 / V17-3
Assessment of site-specific updates	not yet available	

(6) Level 6

The very lowest level includes all raw data and fundamental models, including the "research models" used to test understanding and knowledge consistency. For the safety case, the requirements are to demonstrate that:

- the site data and information are sufficient (i.e. no critical knowledge is missing which could potentially be obtained from the literature);
- the generic knowledge base is comprehensive – no important new developments since H12/H17 have been missed.

The demonstration of completeness is acknowledged to be difficult in all related fields and hence this must be considered as a challenging goal of the KMS. It needs to be emphasised that, in the highly sensitive area of radioactive waste disposal, lack of completeness of a knowledge base can cause important loss of credibility – even if the topics involved have no direct safety relevance.

This also includes large amounts of knowledge which is not used directly to support the safety case, but is important to ensure more general acceptance in terms of credibility, as required by the safety strategy (Figure 2-8). Some of the specific work which is carried out to fulfil this requirement is discussed in the following section.

Overall, it is clear that the PIA safety case would be based heavily on H12 and subsequent, rather generic R&D, due to the limited extent of site-specific data that will be available and the large uncertainties associated with it. At later stages, particularly at the very important decision point of selecting DIAs, a much more rigorous safety case would be required, which would need considerable advances compared to H12.

3.2 Further R&D requirements

The analysis of safety case requirements allows many key areas of knowledge to be examined and gaps identified which can be the focus for future R&D. Nevertheless, this is not complete, as implementation of a HLW repository programme has further requirements that need to be supported by knowledge development programmes. The rationale for integrating all of these within a single KMS is that, again, the base knowledge required often overlaps with that required for the safety case and hence a single KMS is not only more efficient, but it also ensures consistency of the knowledge used. These requirements can be broken down in terms of the user involved.

(1) Special requirements of the implementer

With the requirement to possibly characterise a number of sites in parallel and develop projects which are not only safe but also run within programmatic constraints (time, budget, etc.), there are a number of distinct areas where knowledge is required, including:

- state-of-the-art site characterisation technology;
- state-of-the-art construction technology;
- design plans for a site URL;
- operational practicality / optimisation;
- … .

Clearly, there is a lot of overlap with issues already covered above. Nevertheless, the requirement to optimise procedures which are extremely costly, while maintaining very high levels of confidence in safety, requires that any developments should be extensively tested for robustness in terms of low risk of failure, "failing safe" and ease of recovery from, or remediation of, failure. Inevitably long lead times require that multi-decade planning of specific R&D may be needed.

(2) Special requirements of the regulator

In the short term, the main goal of the regulator is to establish the required structure of safety goals and guidelines. In this respect, knowledge is required to provide:

- guidance to support definition of regulatory guidelines;
- guidance on demonstration of compliance.

The first of these may involve international review of regulations and an evaluation of these in a Japanese context – in particular with regard to areas where there is a lack of consensus (e.g. cut-off times, performance measures in the distant future – EPA, 2005). Possibly more difficult – and less well established – are clearly defined procedures or processes for demonstrating compliance with such regulations. The latter requires a common knowledge base for the implementer and regulator and a standardised nomenclature, to ensure that compliance is feasible and that its demonstration is unambiguous.

(3) Special requirements of other stakeholders

Other important stakeholders include academic and professional bodies, political decision-makers and the public. An important problem has been termed the "asymmetry of information", which is reflected most strongly in the consensus that HLW disposal is safe by experts in this area (e.g. NEA, 1995), the strong concerns expressed by many professional and academic groups who are non-specialist and the common assumption that safe disposal is inherently impossible by politicians, nuclear opponents and the general public.

The requirement for including communication management in the safety case has been discussed previously, but a strongly emphasised communication policy at the point of establishing a KMS could be useful. A particular point worth emphasising for all stakeholders is that communication in terms of a one-way flow of knowledge is no longer considered sufficient and, at the very least, there should be an active, two-way dialogue. Even better, if at all possible, all important stakeholders should be directly involved in the process of making decisions which affect them. To allow such participation, a much more symmetric distribution of information would be a clear goal.

3.3 Implementation of the KMS

Given the vast amount of knowledge involved, efficient management is possible only with a computer-based system. As noted above, the general problem is not unique and available software packages have been developed. Given the complexity of interaction between different types of knowledge, a relational database approach is probably preferable. For requirements management in particular, a number of commercial packages are available which have the advantage of being documentation-based, allowing the very large knowledge base represented by the H12 and H17 report series to be very easily incorporated (particularly as they are already available in electronic form).

A review will be carried out to identify the best option for JAEA's particular needs, but the wish list for the eventual package would include:

- ease of initiation and maintenance;
- security;
- ability to automatically implement change management, including assessment of consistency / compatibility;
- autonomic knowledge generation (inference, data mining, etc.);
- ease of use by a range of users;
- flexibility to evolve with time;
- guaranteed long-term support;
- well established application to similar projects.

This would offer the opportunity to go far beyond knowledge management as currently practised in the nuclear waste management business. Although very ambitious, such powerful tools are credible, based on reasonable extrapolation of the existing state of the art over the decades until a HLW repository will be licensed for operation.

It should be emphasised, however, that such a tool may form the basis of the KMS but, given the diversity of relevant knowledge, it is not sufficient in itself. In particular, this has to be seen in a setting which includes:

- institutional commitment; the KMS is effective only if all relevant knowledge developers commit to providing input. In practice, there may be a wide range of users of the KMS, some of whom may also be knowledge producers. Knowledge would also be provided by other R&D organisations and mined for the general literature (e.g. via internet search engines and agents). To ensure consistency, however, management can only be done by a single organisation – which has to posses the wide experience needed to guide its inevitable long-term evolution.
- managing experience or "tacit knowledge" – as contained in the heads of the workforce. In terms of manpower, it is clear that a HLW repository project will require significant numbers of widely experienced staff, particularly at the time around initiation of operations. Recruitment of highly qualified staff is recognised as a problem throughout the nuclear industry and hence an active programme of manpower development is needed. A HLW repository will be a first-of-kind facility in Japan and, even if a few repositories are operational by this time in other countries, the extent to which experience can be directly transferred will be limited. The multi-disciplinary experience needed cannot be gained in conventional projects and hence this is seen to be a key role of special projects such as large, integrated natural analogue studies and those in underground research laboratories. To attract highly qualified staff, the R&D work involved should be seen to be attractive – interesting, exciting, state of the art; which presents not only a technical challenge in devising such projects but also a communication challenge to younger generations.

3.4 Summary

Based on the requirements identified in Chapter 2, the proposals for structuring the entire knowledge base supporting HLW disposal have been examined for the particular example of establishing a safety case to support the selection of PIAs. Although based only on the documented knowledge base provided by JNC, NUMO and relevant organisations, such structuring indicates not only the areas where strong support is available and needs only to be maintained at the state of the art, but also important gaps where specific knowledge will (or may, depending on the volunteer) be required. This can be directly related to the topics and priorities for the associated R&D programme.

The KMS has been identified as a common resource for all users, to minimise confusion caused by inconsistencies in both basic understanding and, as is often the case, associated terminology and nomenclature. It can be structured to provide the input required by users (ideally interfaced to a RMS), but will be flexible enough to be able to transfer knowledge (in active dialogue) to all stakeholders. A computer-based system will be implemented to provide the essential management functions.

This will, nevertheless, need to be operated within an appropriate quality management system (QMS). Although outside the remit of the present report, specification of such a QMS will be challenging, to ensure that efforts are focused on relevant areas and that it does not simply result in an additional workload without clear benefit (an experience which is common worldwide when traditional QM methodology is applied to what is, essentially, an advanced scientific research programme). In principle, the QMS should be:

- appropriate: focusing on the areas that are really significant;

- accepted: consensus by all involved that the value it delivers is worth the effort involved;
- applicable: not just an abstract concept, but a procedure which really will be adopted and will provide the desired quality output.

The bottom level, however, is that a small quality-assured database is much more valuable in licensing (or any other safety-relevant application) than any amount of undefined data.

Finally, the special requirements of preserving experience through ensuring the required influx of qualified staff and a focused programme of training/experience transfer was emphasised. As a leading R&D organisation supporting the long-term implementation programme, this will be a particular focus for the new JAEA.

4 CONCLUSIONS AND FUTURE PERSPECTIVE

The H17 project represents a status overview of JNC's R&D at the transition point between the generic phase of the Japanese HLW programme, which ended with the H12 project, and the truly site-specific phase which will commence when volunteers come forward, allowing NUMO's staged implementation approach to be initiated. As such, the three technical reports document progress made during this period following the format of past progress reports. However, the present report puts this work in context by outlining a new approach which will be applied to plan, structure and prioritise future R&D.

Fundamentally, there will be a paradigm shift in the supporting R&D programme associated with completion of the movement to an active HLW implementation process at specific volunteer sites. Active site characterisation programmes will be complemented by development of repository concepts tailored to these sites within a structured, stepwise process. This will also be associated with the structural integration of JNC with JAERI to form JAEA – an organisation which will be charged with the management of the fundamental knowledge base to support all stakeholders with interests in the HLW programme (implementer, regulator, academic and professional bodies, politicians and the general public).

To facilitate such changes, a concept associated with a move to a formal KMS has been developed and is documented in this report. The KMS can be structured to interface with a user's RMS. In the absence of such an RMS, the important example of structuring to support development (or review) of a safety case has been illustrated. By mapping the knowledge produced by the H12 / H17 projects against the requirements for the next expected safety case in Japan (to support PIA selection), the extent to which all needs are covered can be analysed.

The KMS will result in a structured procedure for planning, prioritising, coordinating, integrating, quality assuring, documenting and archiving all R&D carried out by the new JAEA organisation. The KMS will also integrate all knowledge needed to support the HLW programme, including knowledge produced by other organisations in the Japanese waste management programme, that produced by foreign partners and advances from wider developments in science and technology. Apart from ensuring consistency, this will aid in focusing R&D programmes by putting work clearly in the context of its use to support the requirements of stakeholders.

In terms of the JAEA R&D programme, some of the characteristics of the paradigm shift will be:

- a move from issue-oriented, bottom-up research to requirements-driven, top-down focusing of effort;
- a transition from a short-term perspective to a programme responsive to requirements developing on implementation timescales;
- a change from the "feasibility demonstration" viewpoint of H3 – H12 to an objective source of knowledge for all stakeholders (with associated changes in documentation and communication approaches);
- phased implementation of a strict quality management system, which should be appropriate to the needs of the end users without introducing inappropriate burdens on the knowledge producers – i.e. focusing of reasonable resources in critical areas.

Such structural changes will inevitably result in evolution of the technical focus of national R&D projects, including:

- focusing resources on areas which have been neglected in the past, e.g. associated with the safety and practicality of construction and operation;
- explicit consideration of "experience" as a key component of knowledge – requiring activities to attract, motivate and train future generations, particularly assuring continuity with present expert staff who will end their active participation before important project milestones;
- establishing procedures to anticipate future developments and evolution of requirements, for example using a "think tank" approach.

In this period of great uncertainty, while waiting for volunteers to come forward, emphasis has to be placed on establishing flexible structures and preparing the background to respond to the intense work programme that will be required if a number of volunteers need to be assessed in parallel. In analogy to the "statement of confidence" required at the end of a safety case, it can now be stated with confidence that the new JAEA will be able to carry out the work required by all HLW programme stakeholders. Further, looking to the future, closer integration of the treatment of different waste streams in Japan seems inevitable – offering potentially major benefits in terms of programme optimisation. The proposed structuring of the knowledge base would facilitate any such expansion of JAEA's remit in the future.

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6 GLOSSARY

Active fault

A fault which has been repeatedly active in recent geological time (within the past several hundreds of thousands of years) and may also be active in the future. Evidence of activity in the recent past is the most reliable indicator of whether a fault zone is active or not.

Autonomic knowledge generation

Knowledge that is spontaneously produced by a high-level information technology system which can identify correlations and relationships in extensive databases.

Backfill material

Material used to infill shafts, drifts and tunnels, commonly composed of a mixture of crushed rock, silica sand and bentonite.

Biosphere

Region of the earth's environment, including parts of the atmosphere, hydrosphere and geosphere, which is inhabited by living organisms; it is usually understood to relate to the human habitat.

Buffer material

Material emplaced between the overpack and the host rock; it is a key component of the engineered barrier system and usually consists of a clay material such as bentonite.

Conservatism

When conducting a performance assessment of a disposal system, the premises for the analysis and/or the data used are selected pessimistically so that uncertainties lead to a reduction in the calculated safety of the system.

Consequence analysis

Assessment of the safety-relevant effects of a particular repository evolution scenario.

Data mining

An information extraction activity whose goal is to discover hidden facts contained in databases. Using a combination of machine learning, statistical analysis, modelling techniques and database technology, data mining finds patterns and relationships in data and infers rules that allow the prediction of future results.

Detailed investigation area (DIA)

The second stage in NUMO's site selection process is to select Detailed Investigation Areas from Preliminary Investigation Areas (see below). Geological characterisation from the surface will continue and be complemented by studies in a specially constructed underground test facility. A final repository site will then be selected from the DIAs.

Engineered barrier system (EBS)

Part of the repository multibarrier system. It comprises the vitrified waste, the overpack and the surrounding buffer material and any other engineered structures specifically emplaced to contribute to containment of emplaced radioactivity (e.g. plugs and seals).

Exclusion criteria

Defined factors which would eliminate a site from consideration as a potential repository host, predominantly associated with geological stability.

Features, Events and Processes (FEPs)

The individual characteristics of a repository and its setting, taking future evolution into account, which can be combined to define evolution scenarios.

Far-field

Region of rock between the repository and the surface which is not directly perturbed by the presence of the repository.

Geological disposal system

A multibarrier system (consisting of engineered and natural barriers) for waste disposal constructed in an appropriate geological environment. It is designed to prevent the waste from affecting either human beings or their living environment at any time in the future. In Japan, the Specified Radioactive Waste (HLW) Final Disposal Act defines “final disposal” as geological disposal at depths greater than 300 m below surface.

Geosphere/natural barrier system

The repository host rock and any surrounding or overlying strata which form a natural safety barrier for waste disposal. The terms far-field and geosphere are often taken as being synonymous.

Geosynthesis

The formal process of integration and synthesis of individual geological measurements to derive the simplified models and data required for performance assessment.

Geographic Information System (GIS)

A computer system for capturing, storing, checking, integrating, manipulating, analysing and displaying data related to positions on or under the Earth's surface.

High-level waste (HLW)

Highly radioactive waste which is separated from spent fuel during reprocessing and then vitrified prior to disposal. In Japan, the Specified Radioactive Waste Final Disposal Act defines “specified radioactive waste” as vitrified high-level radioactive waste extracted or produced from the reprocessing of spent fuel.

Inter-generational equity

Ethical principle which, in the waste management context, states that the generation benefiting from nuclear power should take care of all wastes and that burdens should not be passed to future generations.

Intra-generational equity

Ethical principle which, in the waste management context, states that local communities should not bear undue burdens (or should be compensated for these) when accepting wastes from an industry which has produced regional or national benefits.

Knowledge

In this report, a global term which includes all of the information, understanding and experience relevant to radioactive waste management.

Knowledge asymmetry

Large differences in the understanding of, and information available to, various stakeholders on a particular topic.

Knowledge base

A structured collection of all of the knowledge accumulated to support a particular project, which continually increases and is refined with time.

Knowledge management

Process including all aspects of the development, integration, quality assurance, communication and maintenance / archiving of knowledge – including data, information, understanding and experience.

Multibarrier system

System comprising a series of independent, protective barriers in the repository, consisting of the engineered barrier system (EBS) and the natural barrier constituted by the rock mass.

Natural analogue

A process found in natural (or anthropogenic) systems which is similar to a relevant process occurring in a geological disposal system and provides a means of checking the validity of assessment methods and models.

Near-field

The region which includes the engineered barrier system and the area of immediately surrounding rock which is influenced by the presence of the repository.

Negative FEP

A FEP (generally not fully understood) which is expected to be detrimental to system performance and hence requires special consideration in a safety assessment.

Overpack

Container for vitrified waste (and its fabrication flask) which provides complete isolation for an initial period and thereafter may provide additional barrier roles (e.g. radionuclide sorption).

Performance assessment

An analysis which is carried out in order to determine the extent to which the overall geological disposal system or specific subsystems meet defined goals. When the goals relate to safety, performance assessment is the same as safety assessment.

Preliminary Investigation Area (PIA)

The first stage of NUMO's site selection process is to select Preliminary Investigation Areas from volunteer areas on the basis of literature surveys. The PIAs will be studied by characterisation methods carried out from the surface (including boreholes) to provide a basis for later selection of DIAs.

Quality Management System (QMS)

A formalised system that documents the structure, responsibilities and procedures required to achieve effective quality within a project.

Relational database

A relational database is one in which logical links can be defined between data subsets which facilitates the management of large volumes of inter-related information.

Requirements management (RM)

A formalised process in which the fundamental needs and constraints (requirements) in a programme are documented in a structured way, which facilitates the flow of information and improves the transparency of decision-making.

Reserve FEP

A feature, event or process that is considered likely to occur and to be beneficial to safety and which is deliberately excluded from assessment cases when the level of scientific understanding is insufficient to support quantitative modelling, or when suitable models, codes or databases are unavailable.

Retrievability

This is a special case of reversibility, being the ability to reverse the action of waste emplacement.

Reversibility

Denotes the ability to reverse one or a series of steps in repository planning and development at any particular stage of the programme.

Risk

In a waste management context, the likelihood of any harmful effect occurring due to radiation exposure. Risk is the product of the probability that an exposure to radioactivity will occur and the consequences of such exposure in terms of impact on human health.

Robustness

High level of confidence in a system, process or model due to fundamental understanding, over-design, insensitivity to perturbations or uncertainties, etc.

Safety assessment

Analyses of the effects of the geological disposal system on human beings and their living environment using appropriate indicators (e.g. radiation dose) to quantify radiological influences.

Safety case

The safety case is the complete set of arguments and analyses used to justify the conclusion that a specific repository system will be safe. See also the definitions in the text.

Safety culture

The established environment within an organisation which places top priority on safety rather than other business measures (cost, time, etc.).

Safety indicator

A measure of system performance which is directly related to human health effects – e.g. risk of conventional accident, radiation dose.

Scenario

A combination of FEPs which describes a potential long-term evolution of the geological disposal system.

Sensitivity analysis

An analytical process which systematically investigates the consequences of individual uncertainties or data ranges on the performance of the complete disposal system.

Sustainability

Sustainability is the aim of configuring human activity so that society can meet its needs for the present, while preserving the ability to maintain these ideals indefinitely. Sustainability in the waste management context is often interpreted to encourage recycling and emphasise that the resources utilised for disposal should be commensurate with the benefits gained.

Traceability

The ability, within a project, to access all relevant information, in particular that relating to decision-making.

Transparency

Openness of a project to all key stakeholders.

Uncertainty management

The process of continuous assessment of the uncertainties within a repository project, evaluation of their consequences and focusing of efforts to reduce any risks to project goals.

Validation

The process of demonstrating that a model (or code) adequately represents the system studied by means of comparing model predictions with observations.

Verification

The process of ensuring that the calculations associated with a particular model (or code) actually give the correct numerical answer for the assumptions made.

What if scenario

A what if scenario is a description of the disposal system evolution which goes beyond those expected (or even physically possible) in order to better understand system robustness (e.g. “What if releases from the EBS went directly to the biosphere?”).

APPENDIX EXECUTIVE SUMMARY OF SUPPORTING REPORTS

A1 Supporting Report 1: Geoscience Study

Subsequent to the completion of its 2nd Progress Report (hereafter “H12”), JNC established an overall programme for research and development on the technical aspects of geological disposal in 2001. Based on this programme, JNC has been conducting research and development aimed at achieving a higher level of reliability of disposal technology, consolidating the basis for this technology and advancing safety assessment methods. The two major objectives of the overall programme were defined as confirmation of the applicability of waste disposal technology to the actual geological environment and understanding the long-term behaviour of the disposal system. In the field of research on the deep geological environment, four areas were identified, namely

- characterisation of the geological environment
- long-term stability of the geological environment
- development of engineering technologies for the deep geological environment and
- natural analogue studies

Various activities have been carried out in each of these areas. Progress since H12 in the area of research on the deep geological environment is described in Supporting Report 1. The report contains six chapters, including an introduction (Chapter 1), the role of scientific research on the deep geological environment (Chapter 2), studies on the long-term stability of the geological environment (Chapter 3), characterisation of the geological environment and natural analogue studies (Chapter 4). Chapter 5 looks at the development of engineering technology for application deep underground and a summary of the results from Chapters 3 to 5, together with an outlook to future research and development, is presented in Chapter 6.

The outcome of research and development documented in Supporting Report 1 with respect to the four areas described above is summarised here, together with possible directions for future research and development.

Characterisation of the geological environment

Up to the time of completing H12, the Tono Geoscience Center played a central role in conducting regional hydrogeological studies in the surrounding area. During the same period, research on crystalline rock was being conducted in the Kamaishi mine. Since submission of H12, the majority of the research has been focused in two generic underground research laboratories (URLs), one in crystalline rock and one in sedimentary rock . The former - the Mizunami Underground Research Laboratory project, together with an associated regional hydrogeological study - is led by the Tono Geoscience Center. The latter - the Horonobe Underground Research Laboratory project - is carried out by the Horonobe Underground Research Center.

One of the primary goals of the URL projects is development of technologies for investigation, analysis and assessment of the deep geological environment, which provides a basis for evaluating the applicability of waste disposal technologies to the conditions of the actual geological environment. This was identified as one of the main goals of research and development to be pursued after H12. The research programmes in the URLs will be carried out in a phased manner (Phase 1: surface-based investigations, Phase II: investigations during excavation, Phase III: investigation in drifts) and the reliability and applicability of technologies for investigating and characterising the geological environment will be evaluated by applying them to the in situ geological conditions. This will have the effect of enhancing the overall understanding of the geological environment and improving the accuracy of geological information. At the same time, assessment of the reasonableness of models of the geological environment and development of investigation and assessment technologies will be approached in a systematic, iterative manner. In this respect, the emphasis will be on developing an integrated approach including data acquisition, interpretation, modelling and evaluation. In this approach, in addition to focusing on providing examples of integrated methodologies for understanding the geological environment, efforts are made to summarise as many case studies (including failure cases) and as much know-how as possible to form a knowledge base that will reinforce the technical basis upon which repository implementation and the establishment of safety regulations for disposal will be based.

Investigations in crystalline rock

In order to build up a stepwise understanding of the geological environment, four different spatial scales (regional, local, site and block) were identified for investigation of the crystalline rock formations in the Tono area. The goals of the investigation projects established for the local and site scales were to support the design and construction of underground facilities and associated safety assessment. An iterative approach was taken towards achieving these individual goals.

Regional scale: In order to define a target area for the local scale investigations, analysis of the regional deep groundwater flow system (from recharge area to discharge area) was conducted on several scales. Analyses were carried out for different domains, considering topography and the presence of large-scale discontinuities in the hydrogeological regime. As a result, the deep groundwater flow system in the vicinity of the Mizunami URL was identified and the study area was defined. Assessment of the appropriateness of this approach is underway through the local-scale investigations described below.

Local scale: Investigations on this scale were conducted with the emphasis on evaluation and confirmation of the results from the regional scale, including the groundwater flow system and the selection of the investigation area. This will provide more detailed understanding which can be used to develop and test site-scale models.

Investigations consisted of (i) literature surveys, (ii) airborne and surface-based investigations and (iii) borehole investigations. As a result, the models of the geological environment were revised, allowing a re-evaluation of groundwater flow conditions and definition of the site-scale investigation area. In addition, to confirm the improved reliability of the geological models, the consistency between the results of the groundwater flow analysis and the hydrogeochemical modelling was studied.

A “geosynthesis” methodology was used to integrate and assess the diverse range of hydrogeological and geochemical data available in order to develop an internally consistent model of the site. In addition, the principal results from the investigations include the following:

- High-density electrical surveys are effective for identifying higher-angled discontinuities in the basement granite.
- Spatial distribution and frequency of discontinuities in the basement granite can be estimated from the frequency distribution of the length of measurable large-scale lineaments.
- Results of the local-scale groundwater flow analysis can be validated by conducting porewater pressure measurements and hydrochemical analyses in boreholes drilled along the groundwater flow direction.
- Investigation of the hydrogeological properties of faults cross-cutting the major groundwater flow direction is important in order to define the structure of discontinuities that have a significant effect on groundwater flow

Site scale (block scale): Investigations on this scale were conducted based on the results from the local scale studies and were aimed at enhancing the reliability of geoscientific models by gradually improving the understanding of the deep geological environment. Particular attention was paid to the features which affect groundwater flow, such as faults and preferential flow paths, and to the geochemical and geomechanical properties of the rock mass. In addition, efforts were made to decrease the uncertainties in data and models.

Similarly to the local scale, investigations on this scale consisted of (i) literature surveys, (ii) airborne and surface-based investigations and (iii) borehole investigations.

Models of geological structure, hydrogeological conditions, geochemistry, rock mechanics and material transport have been developed and revised iteratively through these steps. Groundwater flow conditions around the laboratory were estimated and rock mechanical and hydraulic properties around the underground openings have been determined by an excavation analysis.

Again the results of these investigations have been integrated and analysed in a geosynthesis. The challenges foreseen for the next phase and beyond have been identified. The major results of the investigation are as follows:

- For defining the structure of discontinuities that might affect groundwater flow, groundwater flow analysis which includes the effects of hydrogeological heterogeneity is important.
- The investigation of discontinuities based on fracture trace length is considered suitable for modelling hydrogeological features.
- Electrical conductivity logging is suitable for accurate detection of hydraulically significant groundwater flow paths.
- In-situ measurements, such as hydraulic fracturing tests, are effective for characterising the local stress field.

Investigations in sedimentary rock

Activities in the initial stage of the Horonobe URL project consist of (i) selection of the “laboratory construction area” (major investigation area of a few square kilometres) and (ii) investigations in and around the “laboratory construction area”. In the former, the “laboratory construction area” was selected in a stepwise procedure considering a range of important factors. In the latter, as was the case for the crystalline study, individual objectives were set with a view to providing input to safety assessment and the design and construction of the underground facilities. The major results obtained up to 2004 (the fourth year of the first stage of the project) are described below.

Laboratory site selection: The presence of the target geological formation and groundwater conditions (geological environment factors) and the feasibility of safe construction of the research facility (safety factors) were considered as being of prime importance. In addition to these factors, ease of obtaining the permits required for the investigations (societal factor), advantages for layout and construction of the facilities (geographical factors) and aspects of site accessibility and land use planning have been taken into account. The activities include (i) literature surveys, (ii) airborne investigations, (iii) surface-based investigations and (iv) borehole investigations. Based on a stepwise selection approach, the candidate area was narrowed down and, finally, the Hokushin area of Horonobe-cho was selected. The major results include the following:

- Confirmation of the existence of the target geological formation and groundwater regime (geological environment factors) can be supported by airborne geophysical surveys (electromagnetic, magnetic and radiometric).
- However, these methods are not always sufficient for defining the locations of discontinuities, such as major faults.
- Surface-based geophysical and geological investigations can provide important evidence for confirming the effectiveness of airborne investigations and literature surveys.

Investigations in and around the “laboratory construction area”: In order to support the safety assessment and the design and construction of underground facilities, a stepwise approach was used that includes (i) literature surveys, (ii) airborne and surface-based investigations and (iii) borehole investigations. The aim is to improve the understanding of the geological environment and to enhance the reliability of the models of the geological environment by reflecting the data being accumulated. The major results are as follows:

- Based on the literature survey, a sensitivity analysis approach to groundwater flow analysis allows prioritisation of parameters and a general estimate of the direction and rate of flow.
- In terms of hydraulic properties, the geological environment of the Horonobe area has the characteristics of both fractured and porous media.
- In order to understand the characteristics of groundwater flow, it is considered more efficient to assume the geological environment to be a fractured medium, regardless of whether crystalline or sedimentary rocks are present.
- In saline groundwater conditions such as those found in the Horonobe area, the behaviour of Cl^- should be studied as part of the groundwater flow analysis.
- As saline groundwater conditions (including the fresh/saline water boundary) are extensively affected by the long-term evolution of geological environment, analysis of the results should be conducted in parallel with the study/evaluation of the long-term stability of the geological environment, including its geochemical properties.
- For the mechanical properties of highly homogeneous rock masses such as the one at Horonobe, a combination of existing geophysical logging/stress measurement

technologies and standardised laboratory experiments can be applied to determine the distribution of physical properties and the stress field.

- Deformation characteristics in-situ can be simulated by the results of laboratory core experiments and geophysical logging in boreholes. In particular, since they are low cost and less time-consuming, uniaxial compression tests should be performed as far as possible for defining the mechanical properties of the rock mass in earlier stages and to rationalise the investigation programme for the next stage.

Long-term stability of the geological environment

Until H12, research on the long-term stability of the geological environment was conducted mainly to show that there is a wide occurrence of stable geological environments suitable for geological disposal. Based on the trends and frequency of occurrence of natural phenomena in the past, the potential and scale of future events can be discussed.

After H12, in addition to continuing academic research such as nationwide data acquisition and studies on individual events and their mechanisms, the emphasis was placed more on the development of appropriate investigation and assessment technologies. Ongoing research has three objectives, namely (i) development and systematisation of investigation technologies, (ii) development of models used for long-term prediction and evaluation of impacts and (iii) establishing the basis for R&D information via research projects conducted in areas of uplift/subsidence, climate/sea-level change, volcanic activity, seismic and fault activity.

Development and systematisation of investigation technology

Systematic methods for studying the past and present status of natural phenomena have been developed. At present, with a view to final systematisation, development of fundamental technologies and evaluation of the applicability of existing technologies are underway. Investigation technologies for the following five areas have been covered; rate of uplift and subsidence, rate of erosion, Quaternary volcanic and geothermal activity, magma and high temperature fluids at depth and subsurface active faults.

- Uplift and subsidence:

  Through a case study in northern Hokkaido, for example, methods for estimating the rate of uplift in a coastal region, evolution of the former shoreline and horizontal crustal shortening rate have been investigated. As a result, for a period in the order of 50 to 500 ka, geological methods such as analysis of vertical displacement using marine terraces as an indicator and analysis of horizontal crustal strain rate have been found to be more effective than geodetic methods.

- Rate of erosion:

  Burial depth and denudation were estimated by analysing authigenic minerals sampled from sedimentary rocks using boreholes. A method for estimating erosion rates on timescales over half a million years has been developed using data on the paleo-geothermal gradient and determinations of age of maximum burial.

- Quaternary volcanic and geothermal activity:

  The Refractive Index Physical Lobar method (RIPL) for tephro-stratigraphy allows identification of volcanoes as old as Middle Pleistocene. Paleo-geothermal structures and hydrothermal systems can be simulated by thermo-chronological methods.

- Magma and high temperature fluids at depth:

  A systematic methodology was developed that integrates geophysical methods such as seismic tomography with geochemical methods using isotopes of noble gases. The non-volcanic hot spring heat source in the southern Kii peninsula was found to originate from dehydration of a subducting slab.

- Subsurface active faults:

  Subsurface active faults are defined as faults with no surface expression that have shown repeated activity over the last half million years. Methods for studying the distribution of such faults have been investigated. As a result, extrapolation of lineaments and analysis of seismic and digital elevation model (DEM) data were found to be effective for determining the location and geometry of the faults.

Development of models for long-term prediction and evaluation of impacts

In order to develop methods for predicting and evaluating the future evolution of the geological environment due to natural phenomena, a statistical method for defining the frequency of natural phenomena and a numerical simulation of the processes involved have been applied. The four ongoing projects are:

- 3D topographic evolution model: in order to predict topographic changes caused by uplift, subsidence and fault activity, a simulation model has been developed and coupled with a groundwater flow model in order to predict future groundwater flow, taking the Tono area as an example.
- Long-term volcanic activity prediction model: in order to evaluate the possibility of occurrence of volcanic activity using a probabilistic approach, models have been constructed and their applicability evaluated in case studies of monogenetic volcanoes (e.g. Higashi-Izu Monogenetic Volcano Group)
- Model to evaluate the effects of hydrothermal activity: in order to evaluate the thermal flux from deep underground and the upward migration rate of fluids, several different analytical methods have been applied to measured values of borehole temperature profiles and the differences between them evaluated. An analytical code (Magma 2002) has been developed for calculating the thermal and hydrological conditions in the rock mass around a magma reservoir
- Model to evaluate the effects of active faults: in order to evaluate the mechanical and hydrological effects due to fault movement, information has been assembled for developing models of the change in groundwater flow direction and 3D evolution of reverse faults.

Establishing the basis for R&D information

The latest information on state-of-the-art measurement and analysis techniques has been accumulated to provide a basis for development and systematisation of investigation technology and development of the models for long-term prediction and evaluation of the impact of natural phenomena. Research is underway on developing high resolution exploration and monitoring technologies for use deep underground.

Acquisition of nationwide information on natural phenomena has continued since H12. A map of uplift rate distribution in the last 100 ka, a map of landslide topography distribution, a borehole temperature profile database and a geochemical database for hot springs have been prepared and published in academic journals. In addition, a prototype database has been constructed for compiling information on natural perturbation scenarios of the type that is required for safety assessment. This is associated with information on the processes that are relevant for the analysis of migration and general data on the changing geological environment (mechanical, thermal, hydrological and hydrochemical).

For high resolution surveys and monitoring technology for use deep underground, the Accurately Controlled Routinely Operated Signal System (ACROSS) has been developed. Transmitting and receiving systems for seismic and electromagnetic waves and technology for interpretation have been developed which have a higher signal to noise ratio, resulting in higher resolution as well as an extended survey range.

Development of engineering technology for the deep geological environment

The main objectives of the two URL projects, which have been initiated since the publication of H12, are to evaluate the reliability and applicability of investigation technologies to the real geological environment and to establish an engineering basis for the construction and maintenance of an underground facility. The construction of the URL is not, in itself, the main purpose of the project, but is more a means to improve understanding of the geological environment by providing access to it in a facility where experimental research can be carried out. Technology and experience in design, construction, operation and management gained through the URL projects will be applied at the detailed investigation stage of repository site selection. The results will also support the design and construction of the repository, as well as development of the technology for handling and emplacement of the engineered barriers.

Mizunami Underground Research Laboratory

Construction of the URL, with two vertical shafts down to a depth of 1,000 m, was initiated in Mizunami (Gifu Prefecture) in July 2003. The underground facility was designed taking into account considerations of desired depth, complexity of layout and the number of visitors to be expected. Based on information on the geological environment obtained during the initial stage, the stability of the drifts (also in the case of earthquakes), emergency preparedness and the layout of the ventilation system were considered with a view to establishing disaster prevention and safety measures. The appropriateness of the facility design will be evaluated using information obtained during construction and subsequent in-situ experiments. The major findings at present include the following:

- Evaluation of drift stability and design of support systems:

  Drift support systems were tentatively designed using processes developed in H12. 2D and 3D finite element analyses were conducted in order to evaluate the stability of each drift.

- Earthquake-resistant design:

  Considering the characteristics of the Mizunami area, historical earthquakes and active faults in the vicinity, the Tokai earthquake and the Tonankai earthquake were assumed as seismic sources to simulate the seismic waves used to calculate the required mechanical strength of the shafts and concrete lining. Seismic robustness was also confirmed for vertical seismic motion, considering the characteristics of the deep vertical shaft.

- Technology feedback:

A detailed flow diagram of feedback was prepared that combines observation, measurement and field evaluation. The optimum method for evaluating the geological conditions at the drift face, using several different methods to categorise the rock mass, has been investigated.

- Measures against water inflow:

  The requirements to drain inflowing water and to minimise environmental impact have resulted in a focusing of effort to reduce such inflow. Grouting was chosen as the main countermeasure and a plugging programme has been prepared. As it will be time-consuming and expensive to take action after water inflow has started, pre-grouting was considered to be important.

- Key safety measures for designing the URL:

  The concept of an integrated management system combining sub-systems for managing access to the facility, fire prevention, environmental protection and communication was developed. A risk management system for the construction of the shaft was implemented.

  Construction of the underground facility is divided into three stages, i.e. drilling a pit in two stages (the upper and lower pithead) and general excavation. Ground preparation was initiated in July 2002 in the planned laboratory construction area. The three stages were initiated in July 2003, April 2004 and February 2005 respectively. In parallel to construction, geological mapping of the shaft wall, measurement of groundwater seepage and other measurements (rock deformation, stress on the rock support) have been conducted to provide feedback for design and construction. To assess the environmental impact of excavation, hydrological surveys (river flow, groundwater table), measurement of noise and vibration and analysis of water and sediment quality have been ongoing since before the start of construction.

Horonobe Underground Research Center

Initially, measures for maintaining the safety and stability of the drifts and their surroundings were studied, considering the various events that could occur deep underground. Based on these results, as well as information on the geological environment accumulated during the first stage of surface characterisation, the underground facility with a vertical access shaft to a depth of 500 m was designed and construction will be initiated in 2005.

- Design and construction:

  The evaluation of drift stability and disaster prevention (consideration of factors such as flammable gas, drift working environment, risks of fire) is very important in order to ensure safe construction and operation of the facility. Further design requirements for the research projects have also been taken into account. In addition, special consideration was taken of the fact that the facility provides opportunities for the general public to experience the deep underground environment as a contribution to communication with key stakeholders.

- Analysis of drift stability:

  Stability was evaluated based on the results of rock mechanical experiments conducted in boreholes drilled in and around the laboratory construction area up to 2003. The effects of fractures have been taken into account. Hairline fissures, which could be generated by drying out and external stress, have been particularly considered as they could alter key mechanical characteristics. Preliminary analysis using an elastic deformation model was conducted to help categorise construction concerns based on the physical properties of the rock mass.

- Disaster prevention:

  In order to maintain worker safety, in particular considering the risk of generation of flammable gases, a range of possible protection measures and drift management systems have been considered.

Natural analogue studies

In order to help support arguments regarding the long-term safety of geological disposal, natural analogue studies have been carried out in the Tono uranium deposit. These include the characterisation of the long-term behaviour of uranium series nuclides in the surrounding geological environment. In H12, the long-term isolation of such radionuclides in the geosphere was investigated qualitatively, focusing on the uranium series nuclides. Since H12, quantification of the ability of the geological environment to confine radionuclides and definition of factors influencing the confinement function have been identified as further natural analogue study objectives. The results to date are as follows.

Quantification of the radionuclide containment function of the geological environment

Long-term solubility was studied based on the groundwater composition in the Toki lignite-bearing formation that hosts the uranium mineralisation. It was revealed that the major solubility controlling solid was UO_2 (amorphous) and that solubility was influenced by pH, redox potential and CO_2 partial pressure. The long-term solubility of uranium was found to be extremely low.

Definition of factors influencing the confinement function

Iterative data acquisition on the characteristics of geological environment have allowed identification of the major factors influencing radionuclide migration or associated with the preservation of the uranium deposit. By comparing the results of this analysis with the observed inventory of uranium in the deposit and the age of the ore formation, it was observed that the groundwater flow regime had played a particularly important role in the formation and preservation of the ore deposit.
The research in the gallery of the Tono mine was completed in March 2004 and surface-based investigations are continuing.

Outlook for future research and development

In terms of characterisation of the geological environment, both of the URL projects are in the transient stage between phases 1 and 2. The results of phase 1 will be compiled in comprehensive reports shortly after completion. Future research and development conducted at the URLs will be aimed at enhancing the applicability and reliability of relevant technologies to the actual geological environment involved. A stepwise programme will be carried out in order to further define and evaluate the methodologies used to understand the geological environment, as well as to integrate and preserve experience (including problems encountered) and know-how.

The study on long-term geological stability will include development of technologies for determining the past and present conditions of the geological environment and the integration of reliable, comprehensive and systematic methodology. Development of long-term prediction and evaluation models will continue, with research and development of simulation approaches for relevant natural phenomena as well as development of methods for validation of extrapolations into the future. Establishing a comprehensive knowledge base will continue with compilation of the latest geoscientific knowledge and associated information required for safety assessment of natural phenomena and their effects on the geological environment (mechanical, thermal, hydrological, hydrochemical information).

Development of the engineering technology for application deep underground will be carried out in order to confirm and refine the design of underground facilities, based on the information obtained during the first investigation stage, by assessing the impact of the measured data from the second stage. The construction of Mizunami URL was initiated in July 2003 and the underground facility, down to a depth of approximately 1000 m, will be completed in the first half of 2010. In Horonobe, the shaft excavation is planned to start in 2005 and the underground facility, down to a depth of approximately 500 m, will be completed in the first half of 2010

Natural analogue studies will continue to provide an understanding of the correlation between the behaviour of uranium series nuclides and the conditions of the geological environment. This will include an evaluation of the significance for the long-term preservation of uranium ore deposits of crustal movements and microbial influences on the migration and retardation of the uranium series nuclides.

A2 Supporting Report 2: Repository Engineering Technology

The H17 documents the results of JNC's activities in accordance with the current R&D programme (2001-5) which aims to provide a technical basis for disposal implementation and formulation of regulatory guidelines with the following two major global goals:

- demonstrating the applicability of disposal technology to specific geological environments and extending from the base defined more generically in H12;
- further understanding of the long-term system behaviour; integrating information from conventional laboratory studies, in-situ experiments, natural analogues and mathematical modelling to develop confidence in the predictability of the evolution of the repository and its environment over periods of hundreds of thousands of years.

This supporting report of H17 project focuses on repository engineering technology which addresses specific aims and issues set out in the R&D programme, including further understanding of the long-term performance of the disposal system by studying long-term and coupled processes in the near-field environment. For this purpose, work has been conducted at the ENTRY research facility and as part of international collaborative projects. Such studies have looked, for example, at:

- corrosion behaviour of the carbon steel overpack;
- basic characteristics of the buffer material;
- development of THMC (thermo-hydro-mechanical-chemical) coupled models.

In addition to the above research, JNC has also carried out investigations on the long-term behaviour of engineered barrier materials, using natural analogue studies to accumulate data and evaluate assessment methodologies.

Repository closure technologies are an important element of the studies and have been investigated using the facilities available in foreign underground research laboratories. The R&D has also been carried out on low alkaline cement.

The applicability of design methodologies to conditions deep underground has been examined based on the information obtained from the surface-based investigation phases at the Japanese URLs. These research activities allow state-of-the-art knowledge to be incorporated into the design methodologies and databases.

Unlike the H12 report, the intention was not to exhaustively cover all fields relating to disposal engineering technology, but to select some important issues concerning the long-term behaviour of the engineered barrier system (EBS) that are relevant to repository design in terms of process understanding, model development, database development and closure technology.

This report consists of six chapters. Chapter 1 documents the objectives, issues and research procedures based on JNC's overall plan. In Chapter 2, the extension of fundamental EBS database since the H12 report and improved measurement techniques to provide these data are described. Chapter 3 considers the long-term coupled behaviour of the EBS and Chapter 4 evaluates and verifies engineering technologies for the EBS. Chapter 5 discusses the applicability of design methodologies, taking account of open issues remaining from H12, recent international progress and needs arising from implementation of the disposal programme. Finally, further issues which need to be addressed in the next R&D phase are highlighted. In Chapter 6, a summary is given on the progress made in each area since H12 and its relevance in terms of providing timely input to the disposal programme.

Fundamental EBS database

A study of the basic properties of the overpack has shown that build-up of corrosion products has only a limited effect on corrosion acceleration, apparently caused by magnetite. With regard to the effects of cement on the overpack, it has been indicated through experiments in an alkaline environment that passivation could occur at pH values higher than 13 and an improved method for assessing corrosion in alkaline conditions has been proposed. It has been also indicated that the corrosion rate of the welded section is the same as that of the rest of the canister.

To examine the corrosion behaviour of alternative overpack materials, experiments have been conducted under reducing conditions in order to investigate the long-term absorption of hydrogen and embrittlement of titanium and a method for assessing overpack lifetime, taking into account hydrogen embrittlement, has been proposed. Copper corrosion has been also studied experimentally under aerobic conditions to investigate the corrosion modes and the effects of oxygen and sulphate on the corrosion rate. Based on these studies, basic information has been provided for discussing a selection process for overpack materials such as carbon steel, titanium and copper for use in different geological environments.

For the buffer material, the saturation characteristics of bentonite / sand mixtures have been determined using saline groundwater. Data have been obtained on swelling and mechanical properties; such data are freely available and an associated database management system has been implemented. Methods for measuring thermal and mechanical properties have also been studied. The results of the different approaches have been compared and information which could contribute to the standardisation of methodologies has been obtained.

With respect to basic information-gathering on key EBS performance characteristics, preliminary assessment items (what has to be assured), evaluation methods (how to assure it) and evaluation tools (models, databases and test methods) have been studied. Experiments have also been carried out on monitoring technologies for confirmation of EBS performance and emplacement quality.

Long-term coupled behaviour of EBS components

A detailed comparison of existing creep models has been conducted and two models selected for further analysis. A methodology for setting parameters has also been proposed. It has been confirmed by experiments that these two models are suitable for modelling of buffer behaviour.

Sinking of the overpack due to its own weight has been studied using a selected model. The result has shown larger sinking of the overpack than in the H12 report, but the colloid filtration and self-sealing functions of the buffer were maintained and hence this does not appear to present a problem for safety assessment. Models of the long-term behaviour of EBS components, such as the mechanical interaction between buffer and rock, have been also developed.

Regarding long-term rock mechanical behaviour, it has been demonstrated that rock pressure distribution is promising for use as a natural analogue. Using the example of the Wakkanai formation within the Horonobe URL boundary, basic data on mechanical deformation behaviour were obtained and it was shown that, by installing support structures in the initial period after excavation, improvement of the long-term mechanical stability of the cavern can be achieved.

In a study of extrusion and erosion of buffer material, information has been obtained for saline groundwater conditions. With a view to enhancing the reliability of the diffusion model which simulates extrusion phenomena, an X-ray computer tomography (CT) method was employed and the density distribution determined by extrusion into artificial fractures. The viscosity of the bentonite gel was also measured for model prediction. As a result, it was demonstrated that measurements using the X-ray CT method are useful for model validation. It was also shown that the generation of bentonite colloids is not significant in a saline water environment.

For EBS alteration and degradation, a flow diagram was developed for long-term evaluation of the effects of cement and corrosion products on the buffer. The use of low alkaline cement as a material for tunnel support is recommended at the current stage. Based on experimental results, the effects of corrosion products have been shown to be insignificant.

In the coupled THMC study on code development, a prototype code has been developed and validation of the model was attempted using a gallery-scale heater experiment at the Yucca Mountain site and an engineering-scale experiment. Analyses have been performed using this code under the same conditions as for the H12 study and maximum buffer temperature, time for resaturation and pH of the porewater were calculated. The result confirmed the adequacy of the H12 analysis. It was also shown that the accumulation of salt due to evaporation does not have significant effect. A basis for the numerical simulation of the near-field has now been established with the development of this code.

Based on a gas migration test for the buffer, gas effects in saline groundwater have been shown to be almost the same as those in fresh water. With this test, it was possible to evaluate the gas permeability for both fresh and saline groundwater. In order to observe gas migration behaviour, an X-ray CT method was also applied and gas flow through preferential pathways in the buffer was observed. The validity of the existing gas migration model was demonstrated by comparison of predictions with the X-ray CT results. Density measurements using the X-ray CT method have thus been shown to be useful for validating gas migration models.

In studies of EBS shear behaviour, shear experiments have been conducted with a deformation of 80% of the buffer thickness using a 1/20 scale model. It has been confirmed that there is no damage to the overpack due to movement (rotation) of the overpack within the buffer.

In a natural analogue study of the carbon steel overpack, an archaeological survey allowed collection of data from samples with ages spanning a period of 1000 years. The data obtained under weakly oxdising and reducing conditions show that the corrosion assessment in the H12 report was conservative.

Verification of engineering technology

For repository closure technology, data on plug sealing performance have been obtained in underground research facilities in Canada. The data show that the clay plug can maintain a low permeability and a model for demonstrating sealing performance was developed. It was shown that the EDZ becomes a dominant radionuclide pathway if the performance of the intact crystalline rock is good. A methodology has been proposed for evaluating closure scenarios using hydraulic modelling and fault tree analysis.

Experiments have also been conducted on gap filling characteristics for backfill under saline groundwater conditions. The results showed that sufficient sealing performance can be achieved by increasing the mixing ratio of clay to the gravel-based material under saline water conditions.

In the development of engineering materials, a low alkaline cement has been proposed for tunnel support in order to reduce the risk of alteration of the buffer and rock due to the effects of a highly alkaline plume. The low alkaline cement consist of OPC, silica fume and fly-ash, referred to hereafter as high fly-ash silica-fume cement (HFSC).

Performance and quality tests have been carried with various mixtures of OPC, silica fume and fly-ash. HFSC424 indicates a mixture of OPC (40%), silica fume (20%) and fly-ash (40%). Experiments have shown that HFSC424 has sufficient workability and strength to function as a tunnel support. It was also shown that mortar with HFSC424 has a faster pozzolanic reaction in water and the decrease in pH is faster at high temperatures but slower at ambient temperature. It was also shown that it takes a long time to reach pH 11, but the prospects of evaluating the decrease in pH by preliminary model analysis appear to be good.

Confirmation of the applicability of design methodology

With respect to case studies carried out under the geological conditions at the URL sites, investigations were conducted on integrated design flow of a repository, setup of input data on geological conditions for repository design at the stage of surface-based investigations and the design of the disposal facility and, in particular, the EBS. A study on the vertical emplacement concept has been carried out based on the conditions at the Horonobe URL site in the Wakkanai layer (hard shale formation) and at the Mizunami URL site located in the Toki granite formation. To ensure the mechanical stability of the disposal pits, the depth of the disposal facility was assumed to be 450 m at Horonobe and 1,000 m at Mizunami. Based on the results of the study, the applicability and refinement of the design methodology described in the H12 report, recommended methodologies and open issues to be considered were summarised.

In a study on the integrated design flow for a repository, the factors affecting the design and the extent of their effects have been examined considering complex interactions among designs for the facility, EBS and backfill. As a result, and in contrast to the integrated flow described in the H12 report, it was found that the design of disposal tunnel support before the specification of backfill and buffer material, the evaluation of the mechanical stability of the disposal pit, consideration of the need for mechanical support and the backfill design were ranked above the EBS design in the integrated design flow.

Examples of the type of input data for repository design at the stage of surface-based investigations have been obtained from the geological environment characteristics derived from borehole investigations at the URLs. For density and thermal properties, the input data were analysed using a correlation equation of depth dependence, since density dependence of porosity has been confirmed in case of porous media such as the sedimentary rock found at Horonobe. This has not yet been confirmed for crystalline rock such as that at Mizunami. For mechanical properties, a rock mass model was constructed, based on rock classification and material properties that were obtained by integrating the data values for each formation obtained from the borehole investigations. The mean value was applied, because the ratio of initial stresses was found to be constant with depth. Hydraulic conductivities were determined from hydraulic tests and the hydraulic gradient was derived from groundwater flow analysis. Groundwater chemistry was investigated by considering the depth dependence of water composition, with corrections on the basis of a thermodynamic analysis.

For the test design of the disposal facility, the material properties of low alkaline concrete were determined. Based on a design similar to that in the H12 report, the mechanical stability of disposal pits and disposal tunnels and the resultant required disposal tunnel spacing were investigated based on the revised design flow mentioned above. The results of risk studies to support earthquake-resistant design, countermeasures against methane gas and concepts for accident prevention, as well as the computer-aided construction methods studied in the Horonobe and Mizunami URLs, would clearly be key issues in subsequent repository design.

In terms of the EBS test design, the design procedure for the buffer material and overpack was clarified and an individual design flow was proposed. The test design was performed based on input data from the geological environments at the URL sites. As a result, it was clear that the specifications described in the H12 report fully meet existing requirements. The long-term stability of the engineered barriers, based on the specifications in the H12 report, was confirmed by evaluating the long-term mechanical behaviour of the rock and the buffer and also the long-term stability of buffer material, taking into account potential phenomena such as e.g. extrusion and erosion.

For backfill design, the design requirements and issues to be considered in relation to material specifications and sealing plugs were clarified and a preliminary design flow was established. An example of backfill material specifications that are more applicable for the geological conditions encountered at Horonobe and Mizunami was developed.

A summary of the applicability of the design methodology described in the H12 report and potential refinements or extensions derived on the basis of the studies outlined above are presented below:

- With respect to the integrated design flow of the repository, the interactions between individual components such as the overpack, buffer and backfill material and facility design were clarified. A more realistic design flow was presented.
- With respect to the mechanical stability of underground excavations, a technique for evaluating stability using empirical methods based on standard support patterns and realistic evaluation guidelines using a computer-aided construction method was proposed.
- In addition to the study on mechanical stability of excavations and the design of tunnel support using the approach in the H12 report, a study was carried out on the long-term stability of rock under anisotropic stress conditions. This examines the long-term deformation behaviour of rock during the repository construction and operation period and the coupled behaviour of groundwater with the mechanics of porous rock, based

on the characteristics of the sedimentary rock at the Horonobe URL (low strength, anisotropic initial stress and porous medium).

- In the case of disposal pits deep in sedimentary rock with a low strength, there is a possibility that the mechanical stability of the excavation will not be maintained. Therefore, a study of creep behaviour of the rock during the construction and operation period was considered necessary to evaluate the mechanical stability of such pits (without support).
- For crystalline rock, a design based on an elasto-plastic analysis (the same approach as in the H12 report) is applicable to the Toki granite at the Mizunami URL, which has a high strength and a high likelihood of mechanical stability, even though anisotropic stress conditions prevail. Investigation of existing fractures and a design considering the presence of discontinuities were proposed because discontinuities may be a dominant feature in crystalline rock.
- In terms of EBS design, the concept described in the H12 report is applicable. With respect to the evaluation of the long-term stability of the EBS, the credibility of the methodologies used was improved by modification of models and upgrading of input parameters since completion of the H12 report. As a result of this study, the applicability of these methodologies was confirmed.

Next, a summary of points to be considered with respect to investigation of the geological environment, facility design, EBS design and backfill design are presented below:

- In terms of the investigation of the geological environment, it is necessary to assess whether appropriate geological conditions for the support material exist or not, as the choice of materials for tunnel support may be limited due to chemical stability. In the case of crystalline rock, an investigation of the optimum depth of disposal tunnels is necessary to assess whether or not good-quality rock with relatively few discontinuities (fractures) can be found. In terms of data on groundwater chemistry, correction of the results based on a thermodynamic analysis is important because contact with air is likely.
- In terms of facility design (mechanical stability of excavations, support design and disposal tunnel spacing), it is difficult to delineate the wide range of deep geological environments that could be considered for the emplacement of waste packages at the stage of surface-based investigations. Therefore, the design should be revised as required using computer-aided construction methods and compared with data obtained from the site during the construction and operation period. For example, the total thickness of tunnel liner can be reduced by the use of double tunnel supports in the case of sedimentary rock. However, an evaluation of the effect on safety assessment, considering the excavation disturbed zone, is necessary as the double tunnel support process may result in a loosened zone in the rock.
- In terms of EBS design, a reasonable design for the overpack, buffer and backfill material can be achieved by considering the effect of coupled interactions and by focusing on relevant design factors. It is necessary to clarify the relationship between geological environment conditions and associated safety factors. For example, the effect of extrusion and erosion of buffer material is shown to be unimportant under saline groundwater conditions, but significant under freshwater conditions.
- In terms of backfill design, the ionic strength of groundwater may have a large impact on backfill material specifications. Acquisition of data related to self-sealing is

necessary to specify the required content of bentonite in the backfill material, particularly for saline groundwater conditions.

The way forward

For the future, a knowledge base will be developed in order to provide the data and information on the geological environment and repository design required for making the safety case for geological disposal. This knowledge base will represent an important resource for all stakeholders in the Japanese waste disposal programme.

For this purpose, the development of base data, modification of models and development of database systems related to the long-term stability of the EBS will be conducted based on knowledge produced in the geoscientific research programmes centred at the URLs. The aim is to improve the reliability of repository design, particularly for conditions of saline water and soft rock.

Standard procedures for obtaining the data needed for the evaluation will be developed, which will also contribute to the standardisation of results from the range of organisations involved in their production. The applicability of design methodology will be confirmed based on data on the geological environment from the underground facilities and direct in-situ tests of proposed repository structures.

A3 Supporting Report 3: Safety Assessment Methods

The H17 documentation presents the progress made in R&D activities carried out by the Japan Nuclear Cycle Development Institute (JNC) since completion of its H12 project. This supporting report focuses on R&D associated with developing safety assessment methods for a HLW repository. Two global goals for this work were defined in the 5-year R&D programme for the period 2001-2005: demonstrating the applicability of disposal technology to specific geological environments and further understanding of long-term system behaviour.

The key issues are:

1) Extension of nuclide migration databases

The parameters used for H12 radionuclide transport models, including elemental solubility and sorption onto and diffusion through bentonite-based buffer and rock, have been updated and extended to increase the reliability of the databases. In particular, studies on speciation of actinides in a reducing, carbonate system have been carried out. Extended measurements have also been conducted for saline groundwater and sedimentary rock. These updates are reflected in the thermodynamic and sorption databases, which are freely available as part of a policy of transparency.

2) Developing advanced assessment models

This focuses on further understanding of key processes in safety assessment which include:

- groundwater flow and solute transport through fractures/fracture systems, particularly in sedimentary host rock;
- long-term glass dissolution, transformation of solubility-limiting solid phases, and formation of solid-solutions;
- sorption and diffusion in buffer and rock;
- colloid-facilitated radionuclide transport.

The relevant research models have been improved or further developed in this regard. In addition, modelling of hydrogeology and deep groundwater geochemistry has been improved to increase confidence in application of these models to specific geological environments. An approach for biosphere modelling for specific geological environments is also being developed.

Methods for treating uncertainty have been evaluated for groundwater flow and mass transport modelling in heterogeneous media. These studies include hydrogeological modelling with inclusion of sedimentation processes, quantification of uncertainties associated with estimation of groundwater flow and parameter values obtained from in situ tracer experiments.

3) Further development of safety assessment methodology

In addition to development of reliable assessment models and databases, methodology for safety assessment has been developed to increase traceability and transparency within an assessment, improve uncertainty management, promote communication between researchers in different disciplines and facilitate quality assurance. These activities focus on advanced scenario development methods, which allow evaluation of perturbations caused by natural processes and events in a more transparent way. This will facilitate discussion between geoscientists and performance assessors, making uncertainties clearer and improving integration of relevant technical information.

4) Confirmation of the applicability of assessment methods

Using the updated databases, assessment models have been evaluated for specific geological environments in order to confirm their applicability and identify issues requiring further R&D. In this evaluation, the information flow from site investigation to transport calculations is clearly identified and a more formalised procedure for key interfaces has been considered.

It should be emphasised that the R&D activities mentioned above have focused on individual issues which provide a basis for safety assessment of specific sites rather than the comprehensive studies needed to conduct a total system safety assessment.

This document consists of 6 chapters. Chapter 1 introduces the aims and relevant issues for development of advanced safety assessment methods in the light of the present 5-year R&D programme. Extension of radionuclide migration databases from the H12 project is described in Chapter 2. Chapter 3 overviews the development of advanced assessment models. In Chapter 4, this is extended to consider development of safety assessment methodology. By way of a synthesis of the studies described in the previous chapters, Chapter 5 evaluates the applicability of the extended databases and improved assessment models to specific geological environments and identifies open questions, taking account of recent international trends and evolution of the HLW programme in Japan. Finally, Chapter 6 provides a summary and conclusions by highlighting the progress in this area since H12.

Extension of the radionuclide migration databases

The thermodynamic database (TDB) to support radionuclide migration studies was further extended with a view to improving data on bicarbonate complexes of tetravalent actinides. In order to ensure transparency and allow for review, the database (including the updated OECD/NEA TDB) is freely available on the JNC website, in a format applicable to several geochemical codes. As of July 2005, the visitors to the JNC-TDB site numbered over 300, including foreign researchers.

For the expansion of the sorption database (SDB), sorption data for Cs, Se and Sn in a saline environment in sedimentary rock were acquired to allow application to a wider range of geological environments. As for the JNC-TDB, the database is also available on the JNC website and has attracted a similar number of visitors. Approximately 1,200 sorption data measurements published between 1998 and 2003 were collected in the JNC-SDB during its update. In particular, the ionic strength and pH dependency of Kd values for Cs and Am were better established; these improve understanding of the underlying sorption mechanisms - including ion exchange and surface complexation.

Additionally, an index was developed to classify the level of reliability for over 20,000 sorption data measurements. This evaluation of the sorption database provided basic information for the Standardization Committee of the Atomic Energy Society of Japan, which is presently considering the development of a standard measurement method for Kd values for deep geological systems.

Development of advanced assessment models

Advanced hydrological and solute transport models were developed to increase the reliability of the groundwater flow system analysis, which would be necessary in the surface-based site investigation phase. These results are summarised below:

- A nested model which links a discrete fracture network model and a continuum model was developed and its validity examined. It is intended to treat both the regional scale area (where less data are available) and the repository scale area (where more data will be obtained);
- A method for estimating permeability of deep underground formations from pore pressure data was applied during studies in the Horonobe area. The high pore pressure observed in the Wakkanai formation suggested that confining low permeability zones exist. It is concluded that the method is useful for identifying factors which could potentially influence groundwater flow, which could be reflected in site investigation activities and analyses;
- In order to treat coupled geochemical-hydrological processes, a method for modelling groundwater mixing was developed by combining a mass balance technique with backward tracking. This was applied to an analytical study of the impact on groundwater chemistry of tunnel excavation carried out in the Swedish Äspö Hard Rock Laboratory. It is concluded that the method is useful to improve the reliability of hydrogeological modelling and help correct for porosity effects;
- Methods for modelling heterogeneous structures in sedimentary rock were developed to identify uncertainties in existing geological models. Not only quantitative, but also qualitative information has been found useful in terms of increasing model reliability;
- For migration pathways with heterogeneous permeability, a probabilistic finite-element method was applied to estimate such heterogeneity and compared with a Monte-Carlo approach.

The results of studies on hydrological and mass transport processes in fractures are summarised as follows:

- It was indicated (but just from one measurement) that the permeability of a fracture intersection is higher than that of its surroundings, and this could represent a potentially important migration pathway;
- From measurements of the diffusion coefficient of fracture filling material, it was indicated that diffusion was likely not only into the rock matrix but also through such filling material. This implies that the effect of the filling material should be considered when defining parameters for safety assessment based on the results of tracer experiments and an appropriate methodology to define relevant parameters and their uncertainties was developed;
- Modelling indicated that, in sedimentary rock with differing porosity, some fractures would represent preferential pathways while others would not. This suggests that it is necessary to specify the characteristics of significant fractures in site investigation. It was also observed that the correlation of fracture aperture and transmissivity indicated in H12 was applicable to some actual sedimentary rocks.

With regard to geochemistry, themodynamic methods for estimating pH and Eh deep underground were developed using data obtained in the Horonobe URL project and the

Mobara area. A technique for measuring temporal and spatial variations in pH of bentonite porewater was developed. A thermodynamic database on minerals was also compiled, intended for estimating bentonite alteration due to the high pH plume arising from the use of cementitious materials in the repository.

Regarding development of research models for radionuclide migration;

- Studies suggested that secondary minerals arising from long-term glass dissolution would be dominated by analcime for pH > 11 and smectite for pH < 11. It was also found that generation of analcime could accelerate glass dissolution;
- For thorium and uranium, the solubility-limiting solid phases defined in H12 were found to be conservative, since transformation of amorphous hydrous oxide into crystalline oxide was observed in the aqueous system at higher temperatures and low pH range. In addition, further studies indicated that dissolution of an amorphous hydrous oxide (mixture of Np (IV) and U (IV)) could be interpreted by an ideal solid solution model. It was also shown that the dissolution of radium in the presence of barium can be interpreted by a non-ideal solid solution model;
- Although applicable elements are limited at the present stage, it seems possible to estimate Kd values for some rock / water systems and to assess their sensitivity to environmental changes. This is based on mechanistic sorption models;
- Finally, understanding of ion migration pathways within the microstructure of compacted bentonite are under continuous development.

Experimental and theoretical studies have also been performed in order to develop a model of colloid-facilitated radionuclide transport and assess the effects of natural organic substances and microorganisms on radionuclide migration. The significance of colloid filtration was assessed by homogeneous modelling, based on a consideration of the effective clay density. It was confirmed that the measured sorption of Cs on bentonite colloids was higher than that on bentonite powder. A migration code was developed, which is applicable to both fractured and porous media and is able to treat sorption and desorption of radionuclides onto colloids. The code was applied to an in-situ test in a foreign underground research laboratory, and its validity thereby confirmed. Organic matter was identified and its concentration measured in specially sampled groundwater. From measurements of the penetration of organic matter into compacted bentonite, it was observed that the filtration process was facilitated in distilled water compared to synthetic seawater. Stability constants of complex formation for interaction of Th, Np (IV) with organic matter were acquired. For Th, it was confirmed that organic matter did not significantly affect solubility if the carbonate concentration in solution was higher than a certain level. However, it was indicated that radionuclide migration could be facilitated by microorganisms in cases where microbes can effectively travel as colloids.

For advanced biosphere modelling, determining the geosphere-biosphere interface (GBI) to take account of site-specific conditions was assessed. In addition, the H12 biosphere models were extended for different GBIs, including a marine environment, deeper soil layers and different climatic conditions. A procedure for prioritising biosphere data acquisition for the site investigation phase was developed by identifying key parameters. To allow their use as complementary safety indicators, literature data for Japan on the concentration and flux of naturally occurring radionuclides were collected and calculation methods for assessing naturally occurring radionuclide fluxes were developed focusing on relevant catchment areas.

Further development of safety assessment methodology

Handling correlations among FEPs is both important and time-consuming. To improve the efficiency, traceability and transparency of establishing correlations and assessing their significance, a pair of techniques was developed. These are based on presentation of correlations between FEPs in a matrix structure and establishing a hierarchy of these correlations based on their significance for system performance; a computer tool facilitates application and integrates these two techniques.

An approach for eliminating over-conservativeness by importing geological information into the evaluation in a more realistic manner which ensures consistency and traceability was developed.

For definition of parameter distributions, a procedure based on an elicitation protocol was examined and concretised through a trial application. From this study, the importance of sharing information on the variation of solicited parameters was identified.

To quantitatively evaluate the effects of data uncertainty, a probabilistic radionuclide migration model for Monte Carlo simulations which consider uncertainty in a number of data simultaneously was developed. This study also highlighted possibilities for improving reliability and efficiency of uncertainty assessment by complementary use of deterministic and probabilistic approaches.

For sensitivity analysis, efficiency of use and/or combination of multivariable analysis methods (e.g. cluster analysis, multiple regression analysis, discriminant analysis and decision tree analysis) was demonstrated.

The effects of model uncertainty were assessed; alternative models were developed and examined for processes that were either simplified or ignored from the viewpoint of conservatism in H12 (retardation in the EDZ, effect of fractures on glass dissolution). This study indicated possibilities for realistic assessment of these processes, which could contribute to showing robustness of system performance.

A system for managing and integrating technical information in a user-friendly form was developed (JGIS: JNC Geological Disposal Information Integration System). This system aims to maintain consistency between geological investigations, design studies and safety assessment. It should also improve efficiency, by facilitating sharing of technical information between the wide range of R&D groups supporting geological disposal.

Confirmation of the applicability of assessment methods

A structure for the series of activities ranging from site investigation and evaluation to mass transport analysis was examined in terms of application to an actual site. Complex models which import the characteristics of flow paths obtained from groundwater flow analysis for subsequent mass transport analysis were considered based on new simplified models. From this study, a technique for approximating results from a complex model using a simplified model was tested.

Individual data acquisition techniques, system understanding, models and safety assessment methods were applied to both JNC URL projects and overseas underground research facilities. The following were identified as critical issues and topics for future clarification:

- In terms of application of nested hydrogeological models, critical issues involve the development of fracture network models, determination of measurement accuracy for the hydraulic conductivity of water-conducting features by fluid logging and the utilisation of fractal characteristics for the estimation of fracture lengths;
- To estimate hydraulic parameters from measured data, hydraulic conductivities deep underground were estimated from porewater pressures measured in boreholes at the Horonobe URL. A critical issue is the effect of the definition of the transmissivity of faults (sandwich structure of highly permeable and low permeability zones, simple structure of low permeability zones) on the estimation of the formation hydraulic conductivity;
- The importance of understanding the initial conditions of groundwater composition and its evolution, in order to check the consistency of hydro-structural models and variations in groundwater composition, was highlighted;
- It was seen to be important to carefully investigate initial conditions and factors that have an effect on sedimentation when characterising the geological structure of formations subject to sedimentation and compaction processes;
- For estimation of groundwater composition, a method for correcting the composition of groundwaters that were sampled at depth but measured at the surface based on a thermodynamic approach was examined. For this approach, information on formation mineralogy and the need to assess the possible effects of microorganisms and other perturbations are issues to be borne in mind;
- The differing importance of fractures as preferential flow paths in Neogene sedimentary rocks as a function of porosity was implied, which has significance for selection of models and definition of solute transport parameter values. Based on this, the importance of checking the effects of fractures on rock permeability at specific sites and the need for in-situ examination of fracture connectivity was identified;
- For crystalline rock, the need to consider the effects of diffusion into fracture filling materials was identified as being relevant, at least for the interpretation of short timescale tests;
- The importance of understanding rock and groundwater composition to allow sensible definition of distribution coefficients was clearly shown. In particular, the importance of understanding the role of dissolved natural organic matter was highlighted. For the case of limited availability of data for a specific site, a method for estimating distribution coefficients based on an existing sorption database was demonstrated;
- In colloid studies, the following issues should be borne in mind:
    - the need to assess five fundamental colloid characteristics (concentration, stability, mobility, sorption/complexation and irreversibility);
    - the need to sample with minimum perturbation of the underground environment, to avoid the effects of velocity, Eh and pH that have been shown to have an influence on colloid characteristics in groundwater;
    - the need to sample organic matter and colloids with minimum disturbance due to the possible existence of organic matter of the same size as colloids.

- Scenario analysis needs to be developed on a site-specific basis, at a level consistent with the understanding of its geological evolution;
- For uncertainty assessment, utilisation of improved techniques (techniques for definition of parameter distribution, quantitative evaluation of the effect of data uncertainties and abstraction of important uncertainties) with feedback to associated R&D activities was highlighted as a future issue;
- A future issue for biosphere assessment involves improvement of the procedures to narrow down candidates for the GBI based on available information from site-specific investigation by using actual investigations in URL projects;
- Integration of technical information is a critical future issue. This includes accumulation of experience from operation of the JGIS and handling the dramatic increase in volume and complexity of technical information which will result from R&D for actual geological environments.

The way forward

Future R&D studies will focus on the development a common knowledge base, which should be useful for a range of stakeholders, including the implementer and the regulator, as outlined in the Knowledge Management Report. This knowledge base covers all scientific and technical data, information and experience of experts for making a safety case.

Among other things, the strength of the technical basis for safety assessment is a key to increasing confidence in a safety case. In particular, further development of databases for radionuclide migration and assessment model development based on better understanding of key processes are highly important.

The databases and assessment methods should be, as far as possible, objective and transparent to allow their use by both the implementer and the regulator. In this regard, further development and improvement in the technical areas listed above would be useful if carried out by an independent organisation such as JNC, which could maximise output from its extensive infrastructure provided by the two generic URLs, ENTRY and QUALTY facilities.

A new organisation, the Japan Atomic Energy Agency (JAEA) will be established in October 2005 as the result of a merger of JNC and the Japan Atomic Energy Research Institute (JAERI). In order to emphasise the expected role of JAEA as a leading R&D organisation for HLW disposal, introduction of a formal knowledge management system has been highlighted. This contributes to the integration of the work done to support the HLW programme so far and future focused development of new knowledge – for example to support the production, review and public understanding of the safety cases which will be associated with major programme milestones and decision points. Knowledge management can also be useful for identifying further R&D issues in safety assessment, establishing a more formalised linkage with site investigation and engineering technology studies. In the future it can be extended further to take account of the long-term evolution of the HLW programme in Japan and the particular requirements from a range of stakeholders, including the implementer and regulator.