KEY R&D ACTIVITIES SUPPORTING DISPOSAL OF RADIOACTIVE WASTE: RESPONDING TO THE CHALLENGES OF THE 21ST CENTURY

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Ensuring sufficient supplies of clean, economic and acceptable energy is a critical global challenge for the 21st century. There seems little alternative to a greatly expanded role for nuclear power, but implementation of this option will depend on ensuring that all resulting wastes can be disposed of safely. Although there is a consensus on the fundamental feasibility of such disposal by experts in the field, concepts have to be developed to make them more practical to implement and, in particular, more acceptable to key stakeholders. By considering global trends and using illustrative examples from Japan, key areas for future R&D are identified and potential areas where the synergies of international collaboration would be beneficial are highlighted.

KEYWORDS : Disposal, Radioactive Waste, Site Characterisation, Repository Concept, Performance Assessment, Requirements Management System, Knowledge Management System

1. INTRODUCTION

1.1 The 21st Century in Perspective

Radioactive waste management in the 21st century must be seen in the context of the major socio-political and environmental challenges which loom ahead. Probably the most critical challenge results from the rapidly growing world population. The global population was 3 billion in the '60s, reached 6 billion in 1999 and 6.5 billion earlier in 2006. Even if growth tails off as hoped, the population will peak at around 10 billion in the middle of this century. Such growth will not be equally spread around the planet, but very localised and associated with greater urbanisation. Already almost 50% of the world's population lives in cities and further growth is expected, particularly in mega -conurbations (populations >5M) in Asia, Africa and South America.

Population growth will clearly need to be balanced by increases in supplies of food, water and other essential services. However it will occur at a time of rising lifestyle expectations amongst those most disadvantaged, particularly when discrepancies are most evident in urban areas. This will expand pressure on many key natural resources, with associated threats on already strained environmental systems. Nevertheless, the most fundamental requirement is the availability of energy sources that are economic, convenient and cause minimal impact on the environment. Given enough energy, handling most of the other demands is possible – at least in principle. Without sufficient energy, a crisis is inevitable.

Although the stable populations of some developed countries allow many options for increased energy efficiency and use of "alternative" sources (wind, solar, biomass, etc.), the areas with greatest population growth in expanding megacities will need to rely predominantly on fossil, hydro and nuclear power. Given the inherent limitation in the number of locations in which new major hydro-power facilities can be developed (and environmental concerns about such developments), the potential here is restricted. Resources of the most convenient, less environmentally problematic fossil fuels (gas and oil) will be severely depleted by the middle of the century. Although coal, oil shale and tar sands offer much larger supplies, utilisation of fossil fuels may be more tightly constrained by concerns about climate change caused by greenhouse gases.

In the absence of some completely novel breakthrough, therefore, there seems little alternative to massive expansion of nuclear power – both for electricity generation and, possibly, other energy applications (e.g. hydrogen production). Indeed, this situation is becoming increasingly evident to politicians and the nuclear stagnation of the last couple of decades contrasts dramatically with ambitious plans for a nuclear renaissance. This situation is a critical boundary condition for planning nuclear waste management strategies for the 21st century and hence setting R&D priorities.

1.2 The Expanding Role of Nuclear Power

As radioactive waste is generated predominantly by the nuclear power industry, developing scenarios for expected arisings (and hence repository requirements) involves consideration of:

- The evolution in total generation capacity;
- The extent of reprocessing;
- The development of advanced reactors / fuel cycles;
- The role of fusion.

From the above considerations, a common planning assumption in many counties - that nuclear power will be phased out at the end of the lives of existing plants - may be considered increasingly unlikely. Even the assumption, in countries with low population growth, that nuclear generation will continue at existing levels is now being questioned, as a need is seen to replace fossil plants, due to uncertainty in long-term supplies (oil and gas) and global warming concerns. Countries with expanding populations and improving lifestyle expectations are already considering extremely ambitious nuclear expansion – e.g. China is currently planning to install 2-3 GW(e) of new nuclear capacity every year for at least the next 15 years and, according to some projections, could have a nuclear park almost equivalent to today's world total (~350 GW(e)) by the middle of the century (e.g. [1]).

The evolution in world nuclear capacity has an important bearing on national waste management strategies, as the global demand for uranium influences prices, which, in turn, affects the commercial viability of reprocessing. Although some countries have selected a policy of reprocessing due to sustainability or energy independence goals, it has been opposed elsewhere due to arguments about its commercial viability and concerns about the potentially increased risk of nuclear weapons proliferation. The first issue is related not only to U costs, however; a significant part of the economic argument relates to the costs of the reprocessing operation itself and of the management of resulting wastes. Here there is clearly potential for improvement, developing cheaper technology which produces smaller quantities of better defined wastes. The reprocessing technology could also be modified to reduce the risks of proliferation by ensuring that separated fissile material is in a form unsuitable for weapons use.

Reprocessing has already been successfully combined with use of resulting MOX fuels in many reactors. Repeated cycles of reprocessing, however, lead to U and Pu with isotopic compositions unsuitable for use in conventional light water reactors. If there is a desire to utilise resources of fissile fuels more efficiently, advanced fuel cycles need to be developed – e.g. using breeders and other types of fast reactors that can burn a much wider range of actinides. Such fast reactor fuel cycles produce a significantly different spectrum of wastes from those resulting from current nuclear programmes, which may present novel management challenges.

When looking over timescales of decades, a further factor to be borne in mind is the potential role of fusion power. Although progress towards commercial implementation has been painfully slow, there is huge potential for this power source to fill some (or all) of the energy gap developing during this century. Predictions about fusion are notorious for proving wrong, leading to the observation that "fusion is the power of the future – and always will be!" Nevertheless, commercial power plants might be expected to become operational within the next couple of decades and this energy source might be a major component of the energy mix by the middle of the century. Although the waste handling problem may be less for fusion than fission, the characteristics of resulting radioactive wastes will be very different and, in case of significant expansion of this power source, established management strategies should be in place in good time.

1.3 Waste Disposal

While the future of nuclear power clearly influences the development of waste management strategies, the inverse is maybe more critical; the development and implementation of waste disposal projects will help determine the acceptability - and the extent of implementation – of future nuclear power programmes. Despite the fact that high profile accidents (Three Mile Island, Chernobyl) were predominantly responsible for the decrease in acceptance of nuclear power, the perceived absence of a proven management option for waste (particularly vitrified high-level waste (HLW) / spent fuel (SF)) is now seen as the "Achilles' heel" of the nuclear industry. Indeed, such concerns have led to significant investments in alternative management options (transmutation, indefinite storage, space disposal) which, from a purely technical viewpoint, offer no chance of providing a safe alternative to geological disposal based on existing technology or any expected development thereof.

The widespread concern about the disposal of radioactive wastes contrasts dramatically with the consensus within the industry that such disposal is practically feasible, demonstrably safe and economic. It is true that, for higher activity wastes, repository implementation was not pressing due to their small volumes and the advantage of delaying emplacement to allow radioactive decay to reduce thermal output. Nevertheless, most national programmes have been significantly delayed due to public opposition, to the extent that some are effectively stalled. To support future nuclear power development, clear progress in repository implementation is needed.

A past problem was the tendency to use a closed, technocratic approach for the key issue of repository siting. The many failures due to resulting local and regional opposition have led to approaches which are more open and involve direct consultation or dialogue with concerned stakeholders. In extreme cases, this has led to the previous approach of active nomination of sites being replaced by a volunteering process, where the initiative lies with the host community or region.

Increasing the role of a wide range of stakeholders may increase acceptance, but makes the job more difficult for those developing repository programmes and planning supporting R&D. In particular, "dialogue" is, by definition, a two-way process and hence the implementer must be prepared to respond to the wishes of the stakeholder. It is not enough to argue that common popular desires, such as monitoring (or inspection), ease of retrieval, extended institutional control, etc., do not contribute to post-closure safety and make implementation more difficult and expensive. If these wishes reflect real concerns, everything possible should be done to address them. If conventional designs are incompatible with such wishes, then alternatives should be investigated. The implementer certainly needs to ensure that repositories are safe and are not unreasonably expensive, but minimising the worries of local communities also has to be a clear, top-level goal.

Different variants of site volunteering are being considered in several national programmes. This brings special challenges for the site characterisation teams and also requires particular flexibility on the side of the repository engineers. There is a wide diversity of designs that can be shown to provide wide safety margins in different siting environments (see section 2.2.1.). Nomination procedures have tended to favour sites where characterisation and design will be easiest – with emphasis on choosing "better" sites. For a volunteered site with good local support, the question is whether the site is "good enough". At early stages, this might mean living with considerable uncertainties and designing around problems.

Whatever siting approach is used, the process needs to be open and transparent. For the general public, this means more active education and improvement in presentation of the key issues, so that they can participate more actively in – and thus buy into – the decision-making process. Repository projects will also be increasingly subject to review by technical groups with specialist knowledge in relevant areas, even if not directly in the disposal field. The procedures for developing safety cases thus needs to be clear and to be based on quantitative analysis using computer codes and databases which are demonstrably state-of-the-art and fully quality assured.

1.4 R&D Priorities

By considering the boundary conditions outlined above, the requirements for future progress in the nuclear waste management field can be determined. Given such requirements and an idea of the timescales over which repository projects will be implemented, key R&D needs can be listed and prioritised. Some of the R&D goals are clearly achievable based on current technology. Others will require novel developments and hence are inherently more difficult to plan in detail. Nevertheless, when the issue is important, R&D should be initiated even if expected development times may extend over decades. Indeed, by distinguishing between generic needs and those which would be more programme-specific, a list of trickier topics which could be handled more efficiently on the basis of international programmes can be derived.

It is likely that the nuclear industry will become more internationally coordinated with time (Figure 1) and this is also likely to apply to radioactive waste management. For smaller nuclear programmes, this could even involve regional or international disposal projects [2]. However, for all countries involved in radioactive waste R&D, much could be gained by coordination to make best use of expensive research facilities (e.g. underground research laboratories (URLs)) to optimise production and sharing of knowledge and to train the increasing numbers of both specialist and generalist staff needed to implement repositories.

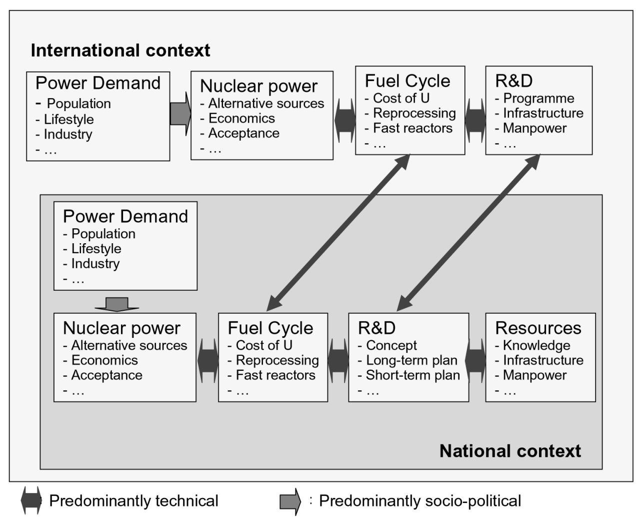


Fig. 1. Inter-relationship of National and International Boundary Conditions for Radioactive Waste Management Programme

This paper will now consider the key technical challenges in further detail, with the aim of identifying the most critical areas for R&D. Although a global perspective will be maintained, particular issues relevant to Japan (and hence, probably, also much of South East Asia) will be identified and areas showing potential for expanded collaboration highlighted.

2. GENERIC R&D CHALLENGES

2.1 Inventory Scenarios, Quantification Tools and Databases

2.1.1 Inventory Scenarios

The definition of waste sources and their classification is a key element of any disposal programme. Without a proper inventory of radioactive waste arisings, including their chemical, physical and radiological properties, it is not possible to design or assess the safety of any proposed facility for the handling, storage or disposal of these materials. Such an inventory should document all existing radioactive wastes and establish credible future scenarios for waste production. Especially in larger, longer established nuclear programmes, even the former can be difficult due to the great diversity of sources of radioactive wastes. The latter inevitably requires a somewhat subjective evaluation of future developments, which, as noted above, must consider both national and international boundary conditions.

For example, Japan has a large nuclear power programme with a total installed capacity of 49 GW(e), generated by 55 operational nuclear power reactors, which represents about one-third of total electricity production [3]. Fuel cycle facilities include an enrichment plant, fuel fabrication facilities, a reprocessing pilot plant, a commercial reprocessing plant (which is currently under test operation) and a low-level waste repository. The existing fuel cycle wastes are reasonably well defined, although a problem is ensuring the consistency of sub-inventories from the different utilities and organisations involved.

Radionuclides are widely used or generated in nuclear medicine, industry and research applications (“MIR” wastes). Japan has a particularly extensive nuclear R&D infrastructure with research / test reactors and a range of particle accelerators, fusion test facilities, hot-cells, etc. Although the total radioactivity of resulting wastes is much less than that from nuclear power production, they are by no means trivial in terms of quantity and may pose particular problems due to their heterogeneity.

It is necessary to mention a further category of wastes that can be problematic to regulate, due to the fact that they arise from non-nuclear industrial activities that involve the handling of raw materials such as rocks, soils and minerals containing naturally occurring radioactive materials (“NORM” wastes - Naturally Occurring Radioactive Materials). The processing involved may result in “technologically enhanced” concentrations of radionuclides, which can reach levels equivalent to fuel cycle wastes allocated to geological disposal (e.g. radium-scales in oil and gas pipelines). The regulation of these materials differs from country to country and has only relatively recently been identified as requiring some measure of control to ensure the correct level of environmental protection. Despite this, this type of waste is currently not controlled in a manner consistent with wastes containing similar levels of radioactivity arising in the nuclear industry.

There is no doubt that an integrated inventory containing all existing fuel cycle, MIR and NORM wastes would help optimise and ensure consistency of waste management and disposal policy. Such an integrated inventory does not yet exist in Japan – or in most other countries – although its production is clearly recommended by the IAEA (e.g. [4]).

To be useful for planning facilities that may operate until the middle, or even the end, of this century, an inventory should also attempt to estimate future waste arisings. Future MIR and NORM wastes might be estimated by extrapolation of historical arisings, but fuel cycle wastes are critically dependent on policy with regard to nuclear power production.

Japan’s overall strategy for the nuclear fuel cycle currently envisages [5]:

- An expanding role for nuclear power; contributing to stable energy supply, reducing emissions of greenhouse gases and decreasing reliance on imports of fossil fuels;
- A commitment to reprocessing spent fuel (SF); recovered U and Pu being fabricated into MOX fuel which is burned in existing light water reactors (LWR) - pluthermal;
- Commencing commercial use of fast reactors around the middle of the century; allowing burning of a wider spectrum of actinides in MOX fuel and also allowing breeding of fissile material from depleted uranium (DU) resulting from the enrichment process;
- Implementation of fusion reactors when these become commercially viable.

As yet, however, this strategy has not yet been examined quantitatively to develop waste arising scenarios, but this is a clear requirement for optimising the future waste management programme. Ideally, this could be taken further, providing feedback on how this strategy could be modified to reduce the production of waste or, at least, minimise production of material that is more problematic to dispose of.

2.1.2 Inventory Development Tools and Databases

Even for existing wastes, the extent to which they can be directly characterised is limited by practicality, cost and exposure to workers. Individual measurements are thus combined with models of the generation of the waste or empirical correlation factors in order to develop inventories which include all the required radioisotope, chemical and physical characteristics of raw and conditioned waste. Such models are formalised in codes that can also determine property changes (e.g. isotope concentrations, thermal output, radiogenic gas production, etc.) as a function of time, accounting for radionuclide decay / ingrowth.

In general, existing HLW/SF inventory databases are reasonably complete. Major uncertainties are associated with possible future changes in waste (e.g. due to higher burn-up of fuel, use of MOX, introduction of fast reactors, changes in reprocessing technology, etc.). In principle, however, for specific nuclear power development scenarios it would be possible to develop model waste inventories, although this has not been done as yet in Japan, except for current light water reactors. Most of this could probably be done with existing tools (e.g. ORIGEN2 [6]), although some effort would be needed to extend databases for novel reactor types and reprocessing procedures.

Inventories of lower activity wastes – especially those outside the nuclear fuel cycle – are generally less complete due to the much greater heterogeneity / chemical complexity of such wastes and the many variables influencing future arisings. At the present time, however, many types of waste may be grouped together and rather simplistic 'average' characteristics used. A combination of analyses of a small number of representative samples, assessment of operational procedures and material balances allows such characteristics to be defined. In terms of post-closure repository performance, it may be useful to identify and group wastes in terms of:

- Content of organic materials (cellulose, plastics, rubber, etc.);
- Presence of complexing agents (EDTA, Prussian blue, etc.);
- Potential for gas-production (i.e. presence of materials such as aluminium and zinc and their surface area to volume ratio; extent of microbiological degradation of materials);
- Content of potentially problematic radionuclides (e.g. I-129, C-14).

Operationally, the characteristics of the packaged, conditioned waste are important for planning repository handling operations and assuring their safety. Characteristics such as the weight and mechanical characteristics of packages, surface dose rates and vulnerability to drops, fire, flooding or other possible perturbations need to be defined.

Ideally, all such information should be combined in an integrated inventory database that can be used to respond to questions, e.g. requests from safety assessors, regulators, etc., in a timely fashion. For examples of state-of-the-art inventories that have been derived in Europe and the US, see e.g. [7 - 11].

Such inventories are, however, rather limited in their ability to form an effective interface with the repository designers and safety assessors. Information flow tends to pass in only one direction – the inventory effectively defining a boundary condition for repository concept development. As programmes mature, however, a two-way flow could lead to significant optimisation. For example, feedback from performance assessment (PA) can help identify areas where increased characterisation provides maximum benefit (e.g. definition of speciation of C-14 in certain waste types) or where improved conditioning could be valuable (e.g. improved immobilisation of I-129).

In the past, individual waste types were defined to allow potential gains of locating them in different parts of a repository to be assessed (e.g. [12, 13]). Potentially, this could be taken further, to allow benefit to be taken by combining different wastes within a particular disposal cavern (e.g. [14]) or, indeed, co-disposing of different wastes within a single package (e.g. [15]). In this regard, there is a grey area with considerable overlap between inventory development and optimisation of packaging for disposal (e.g. [16, 17]).

It is also necessary to look at the implications of assumptions, uncertainties and errors (which are often implicit and unquantified) in any inventory in relation to their potential impacts on repository design and the safety assessment. Errors occur in all work, but these can be reduced (and managed) by a strict quality assurance (QA) regime, for example by checking calculations (a generally straightforward process), confirmation of results by so-called benchmarking exercises (which can be an expensive exercise) and rigorous assessment of the input data (e.g. uncertainties in fission cross-sections, half-lives, etc.).

The challenges in developing improved inventory management tools can be summarised as:

- Integration and expansion of existing management codes and databases to provide a comprehensive overview of all existing and expected wastes;
- Setting such tools within a structure which allows feedback from repository design and PA in order to optimise waste conditioning and packaging (e.g. within an overarching Requirements Management System (RMS) (see later));
- Establishing a suitable Quality Management System (QMS) to ensure that all inventories will be rigorous enough for licensing purposes (N.B. future licensing may be set within an environmental impact assessment structure, which could additionally require demonstration of optimisation).

2.2 Integrated Repository Design Systems

An important constraint on a repository design is the range of wastes intended for disposal. These are often classified according to their radionuclide content, taking into account the type of radiation which they emit and the half-lives of the constituent radionuclides – but, less logically, may also be defined by the waste source. A common example of the latter involves military waste, which may be disposed of separately and under different constraints from civilian waste.

The separation of disposal projects by waste type reflects the different hazards associated with different wastes – those that are more toxic and longer-lived requiring greater robustness of the engineered and / or natural barriers. As noted previously, however, such an approach may be rather simplistic and miss opportunities for optimisation by co-disposing of particular wastes. Further potential for optimisation becomes evident if an integrated design procedure is used – the design engineers working closely with the PA, site characterisation and public communication teams to ensure that the concepts developed are not only safe, but also practical, acceptable and cost-effective.

The situation in Japan is rather unusual; wastes are divided into two main classifications: high-level waste (HLW - i.e. vitrified wastes from reprocessing of spent fuel) and low-level waste (LLW) [18]. This contrast with many other countries, which include very low-level waste (VLLW), intermediate-level waste (ILW) and trans-uranium element bearing waste (TRU) categories. However, the "low-level" wastes are further sub-divided according to their source, to effectively provide equivalent waste classes [18]:

(1) Uranium production wastes which arise mainly at the front end of the nuclear fuel cycle,
(2) Nuclear power plant (NPP) wastes from the operation and decommissioning of nuclear power plants,
(3) TRU wastes containing transuranic elements arising from the operation of reprocessing plants and mixed oxide (MOX) fuel fabrication facilities,
(4) Miscellaneous wastes arising from medicine, industry and research (including decommissioning research and test reactors and nuclear laboratories).

(N.B. NORM wastes and waste from uranium mining are not included in this classification.)

Wastes are also classified according to their envisaged disposal route. Four types of repositories are considered: near-surface disposal (trench and vault-type), intermediate-depth disposal and geological disposal. The management strategy differs for each waste category with different levels of radioactivity. The possible disposal routes for these wastes are summarised in Figure 2.

2.2.1 Concepts, Materials and Methods Catalogues

Studies carried out over the last couple of decades have shown that, under the constraints set by national programmes, many different combinations of waste type / engineered structures and geological settings can provide high levels of safety. In the past, there have been two main types of implementation strategy [19]:

- Given a site (e.g. in the vicinity of waste production), tailor a reference disposal concept to it;
- Assuming a reference disposal concept, select a suitable site that will make its implementation easier.

Except possibly for low activity wastes, both such strategies have often been found to be problematic when applied without allowing for a considerable degree of flexibility to respond to geological surprises, developments in system understanding, changing socio-political boundary conditions, etc. Such "surprises" are almost inevitable in projects of this type, being implemented over periods of many decades. For deeper disposal options, there are always limitations in the extent to which characterisation can be carried out from the surface and hence geological surprises may occur even during construction and operation phases. Near-surface disposal options, on the other hand, may be more vulnerable to changes in regulations and system

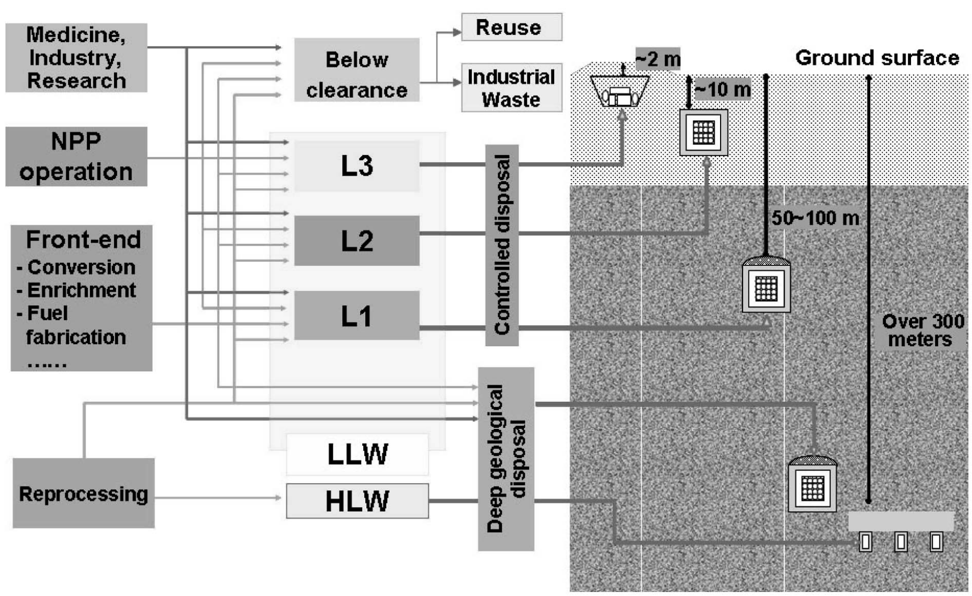


Fig. 2. Disposal Systems for Different Types of Wastes (Excluding NORM Wastes)
(N.B.: Concentration of radioactivity and content of long-lived radionuclides increases L3<L2<L1. Wastes with activity levels above L1, but which do not fall into the HLW category, are often termed TRU.)

understanding. A good example of this would be near-surface disposal sites in coastal locations, some of which have already been operational for decades. Only recently, however, have concerns about the consequences of global warming introduced a new perspective to assurance of long-term performance, which did not exist at the time these facilities were designed [20].

A better approach may be to specify key barrier functions, materials and operational goals and encourage flexibility to refine the design as the project moves towards implementation (or even after operation has commenced), building on experience gained. It is still necessary to define some kind of reference design to serve as a focus for planning, but accepting that this has a model nature can encourage repository optimisation.

In Japan, such a flexible design process is a particular characteristic of the HLW programme, where it is considered essential due to the decision to proceed with siting based on a call for volunteers. Although the original generic H12 concept and its variants, which were established for initial feasibility demonstration [21], still remain a focus and define the main engineered barrier system (EBS) components considered, additional design options have been proposed, taking account of international developments. These repository concept options are summarised in the "Repository Component Catalogue", which aims to maximise system design flexibility [22]. Some examples from the catalogue are shown in Figure 3.

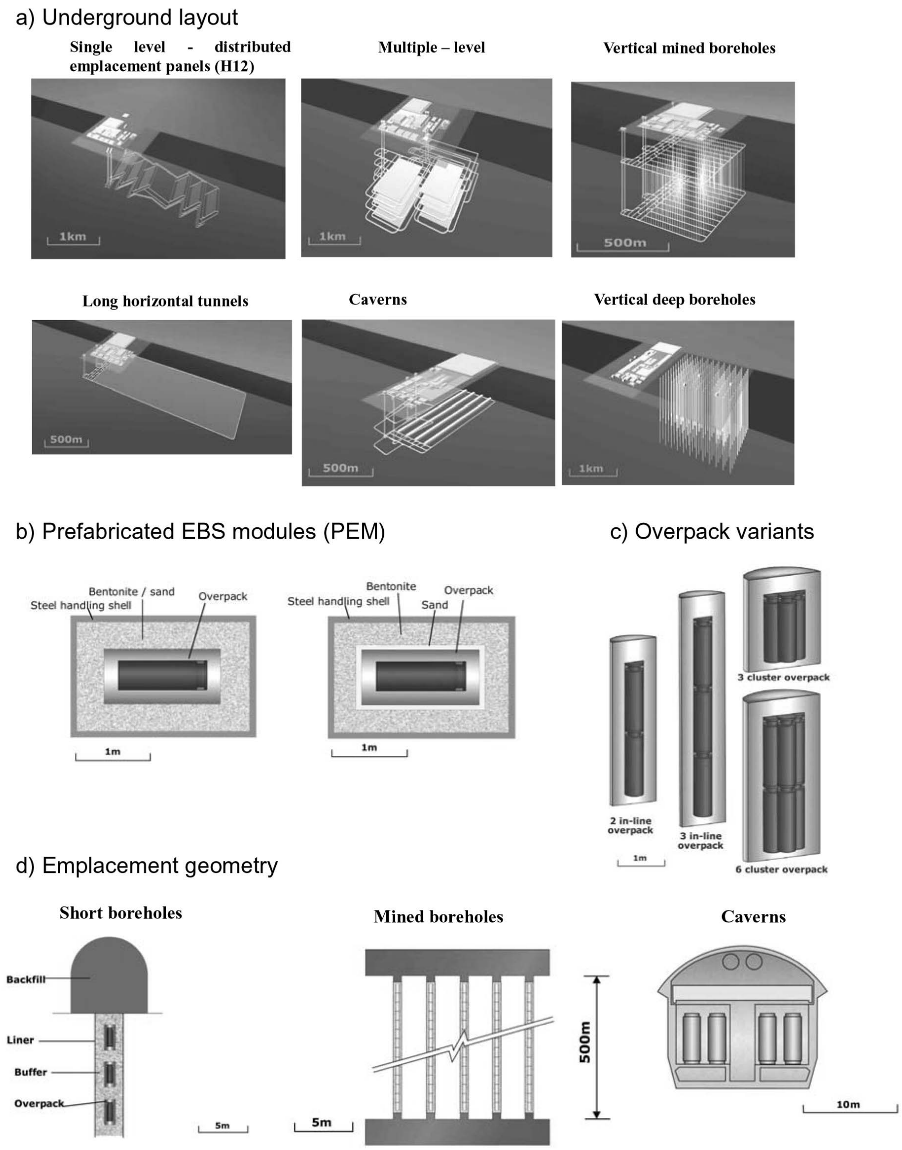


Fig. 3. Examples from the NUMO Repository Concepts Catalogue (after [22])

Although long-term safety is an essential requirement of all designs, a set of factors has been taken into account to address issues bearing directly on the chosen design. For example, the Nuclear Waste Management Organization of Japan (NUMO) has explicitly defined the following "design factors" [22]:

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

These factors are always explicitly considered when designs are being developed, but it is recognised that the weighting of different factors will change as a project moves from a first conceptual phase towards implementation at a specific site (see section 3).

As yet, however, this type of approach has not been adopted for other types of waste in Japan. In particular, detailed post-closure PA for near-surface facilities is not required as an extended (300 year) institutional control period is specified, which allows short-lived waste to decay to insignificance. For deeper disposal of other low- and intermediate-level wastes, a range of fairly standard designs have been proposed, which allow for waste partitioning in different parts of the repository and different engineered barriers depending on its potential hazard. Such designs are not, however, optimised or planned to evolve as site understanding improves – but this could well be a development that will occur in the near future.

2.2.2 Assessment and Optimisation of Designs

In order to develop optimised designs for specific sites, it is important not only to have an integrated database of the information from site characterisation and supporting R&D, but also a mechanism for bringing all of this information together and supporting / documenting decisions with regard to the very wide range of possible design variants. At present, several implementing organisations are investigating formal "Requirements Management" (RM) systems for this purpose [23]. Ideally, RM tools can be integrated with the development of the information database ("Knowledge Management" - KM) and assurance that required quality levels are maintained ("Quality Management" - QM) [24]. Both the information and quality databases should be completely objective and thus form a valuable resource for both the implementer and regulator, if compiled and managed by an independent third party.

In Japan, emphasis to date on developing such a formal approach to design assessment has concentrated on the HLW programme. This is important because the previous H12 project [21, 25-27] did not rigorously assess the practicality of the various design and operational variants or seriously attempt any type of optimisation. Since the basic H12 design was established, there have been a number of important developments, including improved understanding of repository evolution, more sophisticated models and databases, requirements for QA, stricter requirements on practicality and cost-effectiveness, and greater consideration of public acceptance (including social requirements for monitoring, retrievability, etc.). NUMO intends to use an RM approach to help guide extension of designs and identify areas where focused R&D is required.

This latter aspect is important. As a stepwise process moves closer to identification of a final repository site, the details of implementation need to be more clearly specified. It should be recognised, however, that some of the requirements for implementation have long lead times and hence need to be considered early enough that mature technology is available when needed. Initially, repository concept development focuses on the primary engineered barriers, even though a number of other repository structures may have barrier roles – e.g. tunnel liners, borehole caps, backfilling, plugs and seals for tunnels, ramps and shafts. Particularly when considering the safety and practicality of construction and operation, these features may play critical roles. As yet, however, there has been relatively little detailed study of the immediate performance of such structures and their possible long-term interactions with each other (and the primary EBS) (see sections 2.2.2.1. and 2.2.2.2.).

Implementation will allow considerable potential for optimisation and some areas where design improvements are possible have already been identified in the Japanese HLW project – e.g. prefabricating the main components of the EBS, placing several vitrified waste packages in a single overpack. These conceptual options do, however, need considerable study to bring understanding up to the level of more conventional approaches and to clarify any consequences for post-closure safety. For example, optimisation resulting in higher emplacement densities inevitably leads to higher thermal loading and a potentially significant increase in both the maximum temperatures within the EBS and the duration of the thermal transient, which could, in turn, have a large impact on kinetically controlled chemical interactions. The technical background needed to carry out a rigorous cost / benefit analysis within an optimisation study would certainly require significant extension of present-day knowledge.

In principle, the RM and QM approaches developed in the HLW programme could be applied to other waste types and, indeed, the KM base may be largely common to all wastes. Nevertheless, experience is lacking in the application of this formal methodology for L/ILW disposal projects, where the level of complexity may actually be greater than for HLW. This will be a challenge for the next couple of decades.

2.2.2.1 Post-closure Safety

Demonstrating post-closure repository safety, potentially for hundreds of thousands or even millions of years, poses one of the greatest challenges in radioactive waste management. The set of arguments used to address this task is often labelled “the safety case”. Long-term safety is based on the functioning of a suite of engineered barriers within a natural barrier system. It is essential, therefore, that the engineered structures are always emplaced rigorously according to specifications and that previous or subsequent repository operations do not perturb the barrier roles of the geosphere. To achieve these goals, a rigorous QMS is intended to be designed, implemented and further developed iteratively by a multidisciplinary team including those responsible for site characterisation, for design and operation of the facilities and for performance assessment.

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

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

For Japanese HLW, the H12 project [21, 25-27] evaluated post-closure safety using a simple, conservative approach for generic site conditions. A problem with such an approach is that the simplification required is often so great that the analysis is completely insensitive to even rather major variations in site and repository concept properties. In order to fulfil the expanded requirements when dealing with a range of repository concepts and with a variety of sites, major extension of this background is required, including:

- Evaluation of safety during construction and operation of the repository (considering both conventional and radiological hazards) (see section 2.2.2.2.);
- Evaluating post-closure performance more realistically, in order to identify differences between different concepts and different sites;
- Identifying requirements for, or pros / cons of, monitoring and institutional control options;
- Facilitating communication between technical groups involved in site characterisation and repository design, and with other stakeholders.

For the next most active TRU waste, generic safety has also been assessed – albeit in an even more idealised manner [13]. All the topics above also need to be addressed for this waste type – requiring a considerable effort due to its greater complexity.

In Japan, the safety case for the disposal of the remaining lower-activity wastes may depend significantly on the role of institutional control. Nevertheless, it is recognised that there is an international tendency towards stricter evaluation of long-term safety for even such low toxicity materials and hence representative scenarios may need to be assessed in the future – although this does give an increasing discrepancy between the treatment of radioactive waste and non-radioactive waste of similar toxicity.

2.2.2.2 Operational Safety

As pointed out above, most attention in repository programmes in their early phases has been directed towards the assessment of long-term safety. As concepts become firmer and move towards realisation of facilities, the importance of assuring safety during the construction and operational phases grows. Compared to evaluation of performance over geological time periods, assessment of operational safety utilises more conventional methodology. Nevertheless, there are major challenges involved as, while most of the operations considered do not involve radioactivity, public sensitivity means that desired safety levels are similar to those for a nuclear facility.

Detailed planning of construction and operation activities includes an assessment of the risks and consequences of various incidents, accidents and perturbations. Many well established techniques exist for such assessment (e.g. fault trees, event trees) and their implementation can be facilitated by using computer-aided design (CAD) tools, which allow an advance “walk-through” of all such activities. These analyses can feed back to allow decisions to be made about design variants (e.g. shaft vs. ramp access, horizontal vs. vertical emplacement), design details (e.g. liner material /

thickness, use of rock bolts / anchors) or operational variants (e.g. extent of remote handling, extent of parallel construction and operation).

A particular challenge may arise when the requirements for operational safety give rise to a conflict with either post-closure safety requirements or with socio-economic wishes. A typical example of the former could involve use of cement / concrete for grouting, tunnel lining, etc. [28]. Construction engineers may desire extensive use of this well-known material to minimise difficulties (and hence risks) of construction activities. The long-term performance assessors, on the other hand, may want to avoid or minimise the chemical complexities associated with hyperalkaline leachates from cementitious materials.

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

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

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

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

In Japan, the importance of operational safety is recognised and the operational near-surface repository has a very good record in this regard. Working underground with higher activity materials will present greater challenges and hence this is identified as a key area for R&D in both conventional and special underground research facilities.

2.2.2.3 Practicality

Operational practicality is clearly evident for any near-surface repository for VLLW/LLW, as many are in operation around the world. Most of these facilities, unless they contain only very low levels of short-lived radionuclides, depend on a period of institutional control – during which the facility is monitored and, in the event of any degradation of performance, appropriate remediation actions can be taken. The periods claimed for institutional control have gradually increased with increasingly strict regulation of radioactive waste and now lie, for some facilities, in the range of 300 – 500 years. Assuring such institutional control is a novel challenge and, especially in the light of socio-economic and climatic pressures which may emerge in the coming century, is a factor which may require more rigorous assessment in the future (including evaluation of potential control failure scenarios).

Practicality is currently less clear for deep disposal options. Despite the fact that early designs were developed only for feasibility assessment, many national programmes include reference concepts which would be extremely difficult – if not impossible – to implement safely based on existing technology. A common problem involves the practicality of construction of the reference EBS under strict quality assurance controls in an operational repository environment, considering constraints deep underground in terms of restricted space, high humidity, required emplace-ment rate, remote handling, operational safety, robustness to perturbations, etc.

For example, many designs incorporate a compacted bentonite buffer or backfill, which plays several critical barrier roles. Demonstration of buffer emplacement methods to meet defined quality levels (e.g. density, homogeneity) when implemented with appropriate remote operational procedures has yet to be shown in geological environments where the host rock is wet. Indeed, handling of highly compacted bentonite is seen to be very difficult under high humidity conditions and its entire practicality/QA becomes questionable if significant liquid water is present. Neverthe-less, there are certainly ways to engineer around this problem, such as the use of pre-fabricated EBS modules for HLW (or SF) – a concept which was examined in early Japanese desk studies (noted as an option in H12 [26]) but, in the interim, is being increasingly studied internationally (e.g. [29 - 31]).

Current concepts envisage that the main emplacement operations in a mined repository will involve some kind of remote operation, although this has not yet been shown to be feasible with existing technology. The special difficulties of handling radioactive materials underground and the need to be able to recover from any perturbations which might arise during decades of operation lead to a requirement for robustness which, realistically, will require several cycles of iterative design and testing.

Apart from conventional laboratory studies, there seems to be much that could be gained from large-scale, long-term demonstration projects in e.g. URLs, which, in the past, have clearly illustrated the difference between a design that it is possible to implement and one that is truly practical under the boundary conditions in a working repository.

In terms of the practicality of construction and operation, there are other constraints on a repository concept. For example, managing groundwater inflow might involve the use of high quality tunnel (or borehole) liners. Indeed, the use of some form of liner may be required for mechanical stability and a smooth floor needed for handling of large, heavy waste packages. This is increasingly recognised internationally, even in programmes focusing on strong, hard rock. Designs of such infrastructure tend to focus on use of concrete, which raises questions with regard to long-term degradation of bentonite, or even of the rock itself (see section 2.2.2.2.).

In Japan, a number of projects have been initiated in the last few years to improve understanding of the key issues involved with quantitative evaluation of the practicality of implementation of a disposal facility for HLW – including studies of remote-handled waste package emplacement and the overall logistics of material flow in an operational repository. Such work, particularly the former, may require long periods of development to ensure that robust methods and equipment are available when a repository might be implemented. For geological disposal of lower activity wastes, work is less advanced – even though concepts for some critical waste types also include use of compacted bentonite. This is clearly a priority area for the future.

2.2.2.4 Acceptability

It is increasingly recognised that acceptance by local and regional communities is one of the key issues determining whether a project will succeed or not. Although design is predominantly a technical issue, it may be that acceptance will be one of the critical boundary conditions to be considered in the design process (as already noted in 2.2.1.). A great challenge, therefore, is to minimise the extent to which introduction of components or procedures to improve acceptance compromises other performance requirements.

In this context, an international trend is the increasing consensus that enhanced retrievability/reversibility may need to be built into repository designs, both to increase direct acceptance and to allow flexibility by keeping options open for future societies to make use of possible technical advances in waste management and materials technologies. There has been little research on the extent to which such enhanced retrieval provisions – such as delaying the placement of repository isolation barriers – could have negative impacts on safety of conventional designs. Again here, long-term in-situ demonstration experiments could be useful.

In the Japanese HLW programme, an interesting alternative has been examined – involving a complete re-assessment of design to emphasise ease of monitoring and retrieval. The resultant CARE (CAvern REtrievable) concept has many clear advantages, but the operational and post-closure safety case needs more rigorous assessment [32]. Monitoring is also under study as an issue for geological disposal of lower activity wastes, but many of the complex issues involved have not yet been resolved.

2.3 Next Generation PA

2.3.1 Scenario Development Needs

For any specific repository design in a particular siting environment, many different features, events and processes (FEPs) can influence the isolation of radionuclides. These can be represented in a set of scenarios. A challenge is to move on from the current generation of static, generic scenarios. The aim is to better represent varying slow evolution / degradation of the repository barriers for different concepts and sites - i.e. rather than examining the different scenarios as alternative systems, considering directly the changes from the fixed starting-point at time of closure to produce different future conditions. These should also identify clearly the inherent uncertainties involved and major perturbations that can disrupt one or more barriers (due to natural or anthropogenic events).

Improvement of treatment of FEPs will be needed to develop scenarios and provide the framework for their quantitative analysis in a comprehensive, transparent, traceable and understandable manner. For example, time-dependent scenarios will also require an understanding of both how the repository and its surrounding environment might change with time and how such changes will influence the key processes which constrain the release and migration of radionuclides.

In Japan, for all types of waste, evolution processes associated with the active tectonic setting of the Japanese archipelago are of particular concern and have been a focus of work. Nevertheless, further extensive efforts will be needed to develop a consensus on how such slow processes can be quantitatively modelled.

A further area where scenario development is currently focused involves repositories sited in coastal locations. There is considerable concern about the influence of changes in sea-level (both short-term due to anthropogenic warming and long-term during the next ice age), which could cause major changes to regional hydrogeology, geochemistry and biosphere. Developing such scenarios to the point where credible consequence analysis is possible will be a great challenge for the future.

2.3.2 PA methodology Development Needs

Two different levels of models are generally considered: process level models and PA level models. These types of model have complementary roles in linking together site characterisation, repository design and performance assessment. Process models are intended to demonstrate detailed mechanistic understanding of processes. PA models are used to develop an assessment of sub-system performance and overall system performance; in particular, a set of conservative quantitative PA analyses to assess the repository system performance is required to demonstrate compliance with regulatory guidelines.

At a top-level, the following types of model synthesis will facilitate PA calculations:

- Establishing a hierarchy of PA models (sub-system models) and relevant process models;
- Integration of sub-system PA models into a total system performance model;
- Structuring models in terms of their applicability to different scales of space and time;
- Structuring of the parameter-setting procedure so that it can be applied to a range of repository designs and siting environments in a transparent manner.

At the stages of siting and repository concept development, PA models and process models should be as realistic as possible so as to compare and distinguish key differences between repository system options. In some cases, complex and heterogeneous geology may increase the relative weighting of EBS performance within the safety case.

Based on the above points, for Japanese HLW major developments needed are:

- Evaluation of post-closure safety more realistically;
- Dealing with a range of repository concepts and a variety of volunteer sites.

General requirements for these expansions are:

- Incorporation of time dependency into the model chain in order to evaluate scenarios which evolve gradually with time;
- Improved assessment of uncertainties and their development in time and space;
- Increased efforts to test (verify and validate) models and databases (see 2.3.3.);
- Development of presentation formats to make results understandable to a wider audience (see 2.4.).

In principle, such considerations also apply to models for PA of other waste types, although a full assessment of their detailed requirements has not yet been carried out.

In Japan, such synthesis is under consideration, but has not yet been strictly applied within any particular project.

2.3.2.1 Near-field

Particular emphasis may be placed on near-field modelling, as this may be a priority due to the limited geological information at early stages of site investigation. Nevertheless, more detailed and realistic near-field modelling is also required for design optimisation. The tacit focus below is on HLW, although most of the general points are also applicable to LLW.

More realistic representation of the geometry of all components of the engineered barriers (essential for distinguishing between different repository design options) is a clear requirement. This will include both explicit representation of all materials present in repository engineered structures and assessment of any significant interactions between them, including:

- Long-term alteration of buffer material;
- Treatment of thermo-hydro-mechanical-chemical-biological (T-H-M-C-B) coupled processes;
- Perturbation due to repository construction and operation;
- Treatment of EBS / excavation disturbed zone (EDZ) boundary processes;
- PA methodology for the whole repository system, taking into account, e.g. the layout of the repository and the interaction between different releases.

In order to compare different repository design options, a clear need has been identified for bringing the assessment of key components to a similar level. A basic modelling toolkit for such work exists, but improvements are planned to allow differences between repository design options / sites to be assessed more rigorously. Of course, time-dependent model(s) will be needed in order to evaluate scenarios that evolve gradually with time; here improved assessment of uncertainties and their development in time and space will be an important issue.

Extensive R&D will be needed to support such model development, which will evolve in response to progress in the site characterisation work. The challenge is to derive an overall structured R&D programme that provides the input needed for particular milestones in an efficient and cost-effective manner (see also section 3).

A project has recently been initiated to develop the specifications and initiate the development of such “next generation” PA models for the HLW project (e.g. [33]). Extension of this work to consider other wastes will be necessary in the future.

2.3.2.2 Geosphere

More realistic representation of the three-dimensional (3D) geometry of the geosphere, with particular emphasis on the solute transport characteristics of all relevant formations, is needed to compare sites and better define the performance of the geological barrier to support optimisation initiatives. This could include better treatment of heterogeneity controlling both flow-paths and mechanical properties, which may provide a coupling to the performance of the near-field.

Incorporation of time dependency is needed to evaluate scenarios which include changes in sea-level, general and localised (e.g. river) erosion, fault movement, changes in discharge points, etc. The analysis should allow improved assessment of uncertainties and their development in time and space.

As the driving force for such development in Japan is the HLW project, emphasis on such development will increase when site-specific work commences. Nevertheless, even at a generic level, there are some particular issues for other types of waste which require improved assessment methodology – e.g. the influence of a plume of high-pH leachate from concrete on geological barrier performance.

2.3.2.3 Biosphere

Biosphere models are considered as idealised representations that allow potential releases of radionuclides to be put in context. Although there is no attempt to strictly predict future biospheres, examination of a range of future alternatives may be needed to illustrate the consequences of future expected changes – e.g. alternative climates. Time dependent models to evaluate gradually evolving scenarios and improved assessment of uncertainties and their development in time and space may also be important in particular cases (e.g. near-surface disposal).

Developing a Japan-specific biosphere model, which contains the appropriate diet and lifestyle information and an improved representation of the geosphere / biosphere interface, has been recognised as an important goal. Such work will initially be focused on the existing LLW disposal site, but will be extended to other waste types as work becomes more site-specific.

2.3.3 QA, Verification & Validation

Assurance of quality is important in all R&D. This is especially critical as projects move towards licensing. Technical peer review, via publication in respected journals and by independent national or international audit groups, can help ensure that process level models and their supporting databases represent the scientific state-of-the-art. Combining such models within a PA level analysis, however, involves introduction of major simplifications of the natural system and extrapolations in space and time. Here, verification and validation of the models can be very much more difficult and correspond to a challenge which needs to be continuously addressed during repository planning and implementation as part of the process of maintaining credibility.

Inherent problems arise from the slowness of many key processes and the heterogeneity of the systems under study. For example, in-situ tests of radionuclide migration may improve confidence in the migration models or allow their improvement but, to date, experiments have run under relatively high flow-fields and over very small distances, limiting the extent to which models can really be validated. In order to move forward, very long-term (multi-decade) experiments would be helpful - which would allow more representative distances to be examined under more realistic flow conditions. Such validation is required to ensure that PA results are not sensitive to uncertainties in either the data or model assumptions that are used in their evaluation.

Critical areas where further validation is required include:

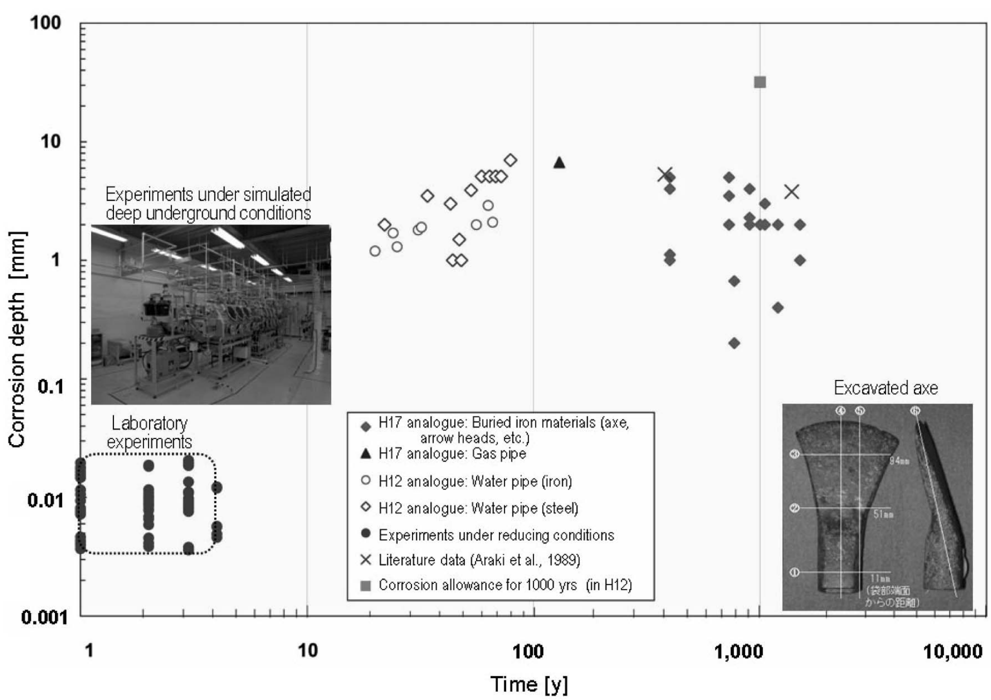


Fig. 4. Integration of Iron / Steel Corrosion Data from Laboratory Experiments and Multiple Analogue Sources [34]

- Use of thermodynamic models to derive elemental solubility limits (and speciation) and evaluate the alteration of EBS materials;
- Solute transport in microporous media (bentonite, clays, concrete);
- Barrier roles of waste matrix and overpack in a low-flow environment;
- Influences of perturbations such as gas, colloids, microbes, organics.

The challenges are considerable, even when an individual, time-independent process is considered. This becomes even more difficult when processes are coupled and time variability is taken into account. As yet, there is little significant effort to address such challenges in most national programmes, but this may be expected to change as technology advances and increasing demands are placed on supporting PA results as projects move towards licensing.

Formal validation cannot be applied for an entire repository system over the full temporal and spatial scales considered in PA, but uncertainty can be managed to some extent by seeking multiple lines of evidence for particular assessment assumptions or parameters. This can involve extending data from theoretical, laboratory and in-situ field studies to including evidence from natural analogues. In particular, laboratory measurements may be well defined, but are generally limited in size compared to repository systems. While field measurements may be larger in spatial scale, boundary conditions are inherently less well defined.

Especially in addressing the issue of timescales, analogue studies play an important role. These analogues are natural (or archaeological) materials and processes which are similar to those considered in PA and are found in relevant conditions. For example, Figure 4 illustrates a simple application where archaeological data on the corrosion of iron artefacts are compared with experimental data. Here, it is noticeable that the long-term corrosion rates from the archaeological samples are very much higher than the laboratory data – reflecting the fact that archaeological artefacts are found in the soil zone, which is generally more oxidising and corrosive than the very deep geological environment. Regardless, the reference corrosion rate used to set a corrosion allowance for PA is clearly conservative – if not over-conservative.

As indicated in Table 1, analogue data are particularly useful if they can be combined with information from the laboratory – ideally from both conventional and in-situ (underground) test facilities. Data from these sources have particular advantages and disadvantages, so that they can be designed to complement each other, together with appropriate modelling studies – which can be either mechanistic or more empirical. It should be emphasised, however, that many relevant processes are more complex than corrosion (e.g. radionuclide solubility, transport) and the demands on analogue studies can be significant. In the past, several major international collaborative analogue projects ran (e.g. Oklo, Cigar Lake, Poços de Caldas, Maqarin – [35]), which were coordinated by the Natural Analogue Working Group (NAWG). Further initiatives to carry out similar projects, which would allow testing of the next generation of codes and databases, would seem to be valuable in the future.

Table 1. Characteristics of Laboratory / In-situ Tests and Analogues

	Laboratory test	In-situ test	Analogue
Subject of study	can be focused on those processes considered to be important	more complex, but realistic conditions, often with coupled processes acting	natural systems and artefacts with evidence of their past evolution under ambient conditions
Initial / boundary condition	can be chosen and controlled	can be partially defined by site selection, but are not simple	uncertain and sometimes hard to estimate
Timescale	typically over days to years	typically over months to decades	over decades to many millions of years
Application of the results	need for extrapolation, integration or making simplifying assumptions	specific to the site or transferable only to similar geological environments or systems	support for assumption in terms of longevity – subject to caveats on system uncertainties
Examples	· leaching from waste matrix · metal corrosion · sorption on defined materials or mineral phases	· tracer tests · studies of thermal and hydraulic evolution	· evidence for longevity of repository materials or systems (e.g. natural glasses, bentonite clay and metals under reducing conditions, uranium ores)

In Japan, a well integrated programme of model testing based on laboratory, in-situ and analogue studies existed for the HLW programme as summarised in the H12 project [21, 25-27]. As yet, however, this has not been extended to focus on the particular concerns of the next generation of more realistic models, which will be needed as a repository project moves towards implementation. There is also a lack of an integrated programme (and, in particular, suitable analogues) for lower activity wastes, which may be a significant challenge in the coming decades.

2.4 Presentation to Key Stakeholders

International experience has shown that involvement of stakeholders is essential to the decision-making process at all stages of disposal programmes. In general, the primary concern of the public arises from general anxiety about radioactive waste, due to a lack of understanding of the issues involved. Indeed, the perception of long-term risks associated with geological disposal tends to be exaggerated, even by technical audiences who are not experts in the PA field. A particular problem is achieving confidence in the passive safety provided by the deep disposal system for geological time periods. Unlike the active safety in conventional engineering systems - such as nuclear power reactors and surface waste storage facilities - passive safety systems (e.g. due to low water fluxes, chemically reducing conditions, robust waste matrices) are hard to explain. Hence, the public may insist on additional design features (e.g. monitoring, ease of retrieval) which are not technically justified, or even risk compromising the safety of conventional designs.

To alleviate this situation, improvement of the presentation of safety arguments to all stakeholders must be seen as a key development area. Such presentation should provide a readily understandable information base, which includes consistent material for both technical and non-technical stakeholders. In this regard, building and maintaining state-of-the-art capacity in graphical presentation of complex information and other user-friendly interfacing methods is a high priority. With the aim of establishing two-way dialogue with stakeholders, information materials need to be combined with experts who are both willing and capable of communication. Indeed, during a repository development programme, which will typically last for several decades, stakeholder requirements are likely to change. It should be noted that responding effectively to such changes requires continuous dialogue between the project team and critical stakeholder groups.

For the particular case of the Japanese volunteer approach to HLW repository siting, establishing dialogue with non-technical stakeholders has been identified as essential to success. Hence two-way communication will be a cornerstone of further R&D studies (i.e. development of a knowledge management system; see section 4.1.), 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 knowledge management system and all potential users [34]. In any case, extension of such initiatives to include other waste types will be a future priority.

3. R&D REQUIREMENTS TO SUPPORT IMPLEMENTATION

3.1 Staged Implementation for Various Siting Strategies

A stepwise repository development approach, with an iterative process of site characterisation, repository design and safety assessment, is internationally accepted and implemented in many national programmes. Through this approach, repository concepts can be tailored to siting environments, taking account of not only long-term and operational safety, but also engineering practicality, retrievability and monitoring, as well as environmental impact and socio-economic aspects (Figure 5). The challenges lie in defining a process of repository concept development that is appropriate and accepted by all stakeholders and which ensures that the knowledge base required to support it is available in an accessible and timely manner.

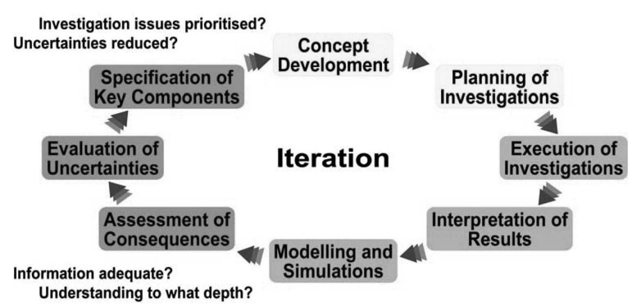


Fig. 5. Iterative Process for Stepwise Development of Geological Understanding and Tailoring the Repository Concept to Actual Sites

In June 2000, the “Specified Radioactive Waste Final Disposal Act” was enacted in Japan to provide an organisational framework for the siting and construction of a geological repository for HLW. A new organisation, NUMO was established to implement the plan, which explicitly requires stepwise implementation. NUMO will proceed with siting initiated by an open solicitation procedure (a call for volunteer host municipalities). Site selection will start from such volunteers and narrow in on a preferred option based on increasingly detailed characterisation work [36]:

- Firstly, Preliminary Investigation Areas (PIAs) will be selected, based on literature surveys (non-invasive investigations) of volunteers;
- Detailed investigation areas (DIAs) will then be selected from PIAs, following surface-based investigations (including geophysical surveys, trenching, borehole drilling, etc.);
- In the final, third stage, detailed site characterisation, including studies in underground investigation facilities, will lead to selection of a site for repository construction.

In contrast, the implementation of the near-surface disposal facility at Rokkasho, where much of the waste arises, was much simpler. The safety case is focused on institutional control, and hence designs have not been modified since original licensing, although some operational aspects have been optimised. The design of the planned intermediate-depth (~50-100m) disposal facility for higher activity LLW may need careful evaluation in the future; knowledge of the site will increase greatly as underground construction progresses and requirements will be better defined when regulatory guidelines are finalised.

3.1.1 Need for a Structured Approach and Requirements Management

Stepwise implementation and tailoring of both design and the site characterisation programme to specific sites may increase acceptance and allow for considerable technical optimisation, but create their own difficulties for the teams responsible for doing this work. The key problem is to ensure flexibility while maintaining programme focus. In the past this was done informally, based mainly on the experience of generalist staff with wide overviews of radioactive waste management. More recently, however, it has been recognised that the increasing complexity of this field and the multi-generational nature of long implementation times require more formal approaches to programme development and associated decision-making.

In the Japanese HLW programme, a structured approach was originally developed for tailoring of repository concepts (designs plus implementation plans and associated PA) to sites. This has since been extended to include the development of site conceptual models, which will form a basis for the assessment of a site's conformity to regulatory conditions, and iterative development of site-specific characterisation plans. The NUMO structured approach (NSA) includes clear decision-making guided by assessment of various hierarchical levels of programme requirements [24]. Thus an RMS is under development as a matter of high priority [37]. The RMS can also help to identify and prioritise R&D issues, which provide essential input for key implementation decision points. Although applied only to the HLW programme to date, the approach and management tools could also be used to aid repository projects for other wastes.

3.1.2 Anticipating Regulatory Requirements

The extent to which regulations and guidelines are already established varies between different programmes. Nevertheless, even when regulations are defined, there is continuing debate at international level on some of the key issues of how to define safety goals in the distant future and how to assess compliance with such goals. It is thus important that technical support is also provided to the regulator, to allow reasonable, practical and publicly acceptable guidelines to be defined. To support the implementer, an approach to assessing site-specific information will be needed to assess conformity with guidelines, in the light of various types of uncertainties. Additionally, a methodology for evaluation of such uncertainties and determining the robustness of the entire repository system will be also needed for presenting and reviewing safety cases.

In Japan, regulations exist only for near-surface disposal, although their development for further types of waste is a high priority. There has been a stated desire for homogeneous treatment of all repository types, although this will be challenging [38]. The site investigations currently underway for the intermediate-depth repository at Rokkasho will be on the critical path for such regulations. Thus, it is important when carrying out technical support work to attempt to anticipate not only how license requirements may initially be proposed, but also how they might evolve with time, so that all critical requirements for R&D can be identified. In this regard, the R&D plan for safety regulations, which are prioritised and issued by the Nuclear Safety Commission (NSC) every five years, provides useful guidance – even if focused on a rather short time perspective [39].

3.2 Site Characterisation Toolkit

3.2.1 Non-invasive Investigations

In a stepwise implementation programme, decisions to go further with more detailed characterisation are associated with increasingly large commitments of resources. Even at an early stage of site screening, it is thus important to be able to ensure that hopeless cases are excluded (which also contributes to establishing credibility). Nevertheless, as the selection process is likely to have high political sensitivity, it is important to demonstrate that the selection procedure is fully objective and transparent, and that potentially viable sites are not wrongly assessed.

In Japan, the procedure for assessing sites is focused on the HLW programme, although this may be later extended to other types of waste. The problems in evaluating sites are particularly acute here, due to the volunteering process and the geological and tectonic complexity of the Japanese archipelago.

To provide background during the period until volunteers come forward, national research on the long-term stability of the geological environment using literature information was conducted, which showed that there is a wide occurrence of stable geological environments suitable for geological disposal. Critical documentation was collated, updated and published, such as the catalogue of Quaternary volcanoes in Japan, a map of active fault distribution in Japan and a map of distribution of denudation rates [25]. Based on the trends and frequency of occurrence of disruptive natural phenomena in the past, the potential and scale of future events were assessed and a prototype database has been constructed, which compiles information on natural perturbation scenarios of the type that is required for safety assessment.

Systematic methods for studying safety-relevant natural processes are being developed, with a focus on:

- rate of uplift and erosion;
- Quaternary volcanic and geothermal activity;
- magma and high temperature fluids at depth;
- concealed active faults.

As an example of this, a systematic methodology was developed that integrates geophysical methods, such as seismic and electromagnetic surveys, with geochemical methods using isotopes of noble gases, in order to investigate magma and high temperature fluids deep underground [25].

In order to develop methods for predicting and evaluating the future evolution of the geological environment due to natural events, a statistical method for defining the frequency of natural events and a numerical simulation of the processes involved have been combined. Four ongoing projects involve development of:

- a 3D topographic evolution model;
- a long-term volcanic activity prediction model;
- a model to evaluate the effects of hydrothermal activity;
- a model to evaluate the effects of active faults.

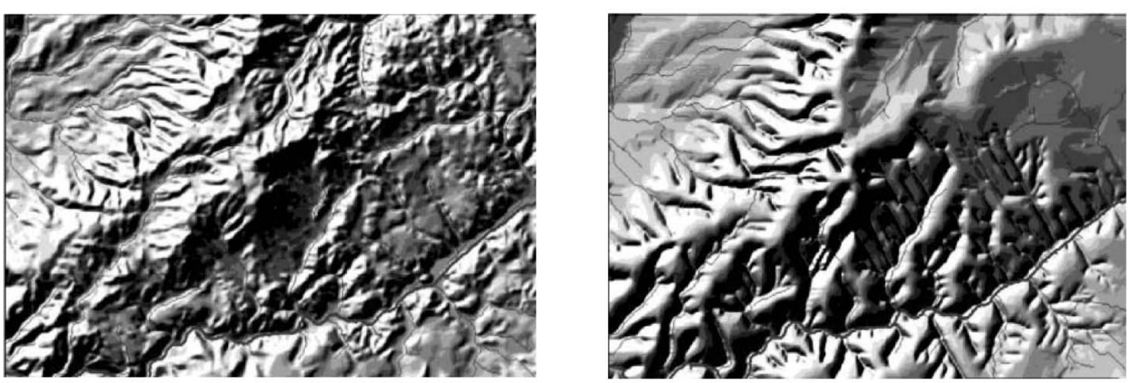
As an example, a simulation method for long-term 3D topographic evolution is under development, based on past uplift / erosion data (Figure 6) [40]. This type of advanced technique can be further linked dynamically with a 3D hydrogeological model simulation to evaluate future changes in groundwater regime – potentially improving realism but also considerably increasing model complexity and the volume of output information produced.

3.2.2 Invasive / Borehole Based Investigations

Field studies, including geophysical surveys and testing in deep boreholes, are expensive, require considerable resources of specialist equipment and manpower and can be disruptive for local communities. It is thus important that such field campaigns are carefully planned to ensure that they achieve all priority goals by specified milestones. Even for a programme which is not under time or budget pressure, field work has to be organised in such a way that specific measurements do not interfere with each other and quality levels are achieved. For the more common case of tight time and budget constraints, prioritisation is essential, as is planning for “surprises” to the extent possible (it is commonly found that literature data can be very limited in their ability to characterise the key features of sites).

As previously mentioned, in Japan a site investigation programme is ongoing at Rokkasho for an intermediate-depth repository. The development of a general site characterisation methodology being carried out by JAEA at two purpose-built generic URL sites could also provide technical support. The locations and conceptual plans of the Mizunami and Horonobe URL projects are shown in Figure 7. The Mizunami URL site consists mainly of Cretaceous granitic basement rocks overlain by Miocene and Pliocene sedimentary rocks. Horonobe lies on Neogene sedimentary sequences underlain by Palaeogene to Cretaceous sedimentary basement.

The URL projects will run over a period of around 20 years, in step with the national disposal programme for HLW. The projects consist of three phases: surface-based



(a) Present topography **(b) Prediction at 120 thousand years in the future**

Fig. 6. An Example of 3D Topographical Evolution Predicted for the Tono Region [40]

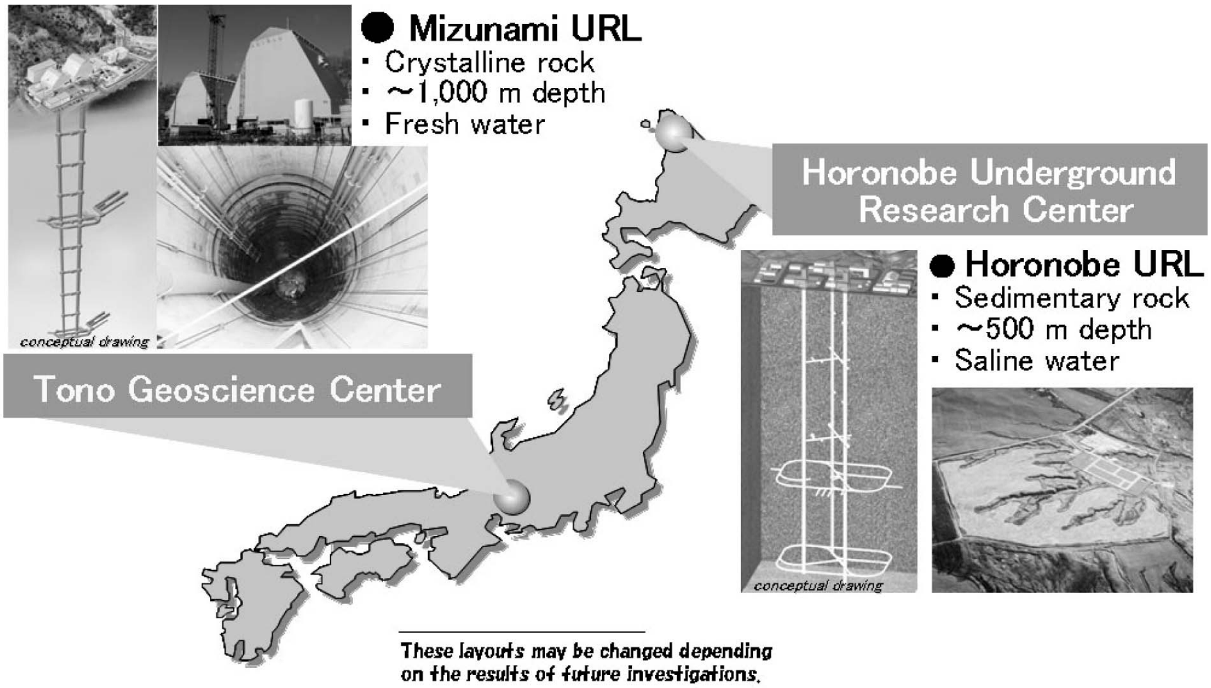


Fig. 7. Locations and Conceptual Plans of the JAEA Mizunami and Horonobe URLs

investigations (phase 1), investigations during excavation (phase 2) and investigations in drifts (phase 3). The URLs provide a wide range of possibilities for underground research by universities and other research institutes, as well as serving as a tool for enhancing public understanding of key issues related to geological disposal. The output obtained from the URLs will be widely disseminated and is expected to make a timely contribution to the disposal programme and to the establishment of safety regulations. Key output includes:

- Techniques developed for characterising the geological environment in a stepwise manner, based initially on investigations from the surface (phase 1);
- Data obtained from investigations during the excavation phase (phase 2), which will serve to verify and refine the results from the surface-based investigations and to characterise the evolution of the geological environment during drift excavation;
- Detailed investigations in the underground facility (phase 3) will contribute to validating and refining geological investigation techniques.

At present, phase 1 has been completed and phase 2 is ongoing at both Mizunami and Horonobe.

A geological environment model has been developed from the information provided by phase 1 investigations using a wide range of techniques. At the Mizunami URL site, lineament analyses, geological mapping, reflection seismic surveying, existing and new shallow borehole investigations and a new deep borehole project were carried out during the period up to October 2004. Crosshole tomography and vertical seismic profiling in a deep borehole were completed by the end of 2004. Continuous improvement of the geological model, based on input from the above investigations, is illustrated in Figure 8.

Based on the geological model, datasets required for further modelling studies have been produced. These datasets include hydraulic conductivities for the upper highly fractured domain and lower sparsely fractured domain of the granitic basement, groundwater chemistry and physical and mechanical properties of all significant formations and rock discontinuities.

Through such phase 1 research at the URL sites, the reliability and applicability of technologies for investigating and characterising the geological environment have been evaluated by applying them to representative geological conditions. Systematic investigation and modelling methodologies were illustrated, including geophysical surveys, borehole investigations, identification of water-conducting features [41] and an integrated modelling technique which includes uncertainty analysis. Research is also underway on developing high resolution surveys

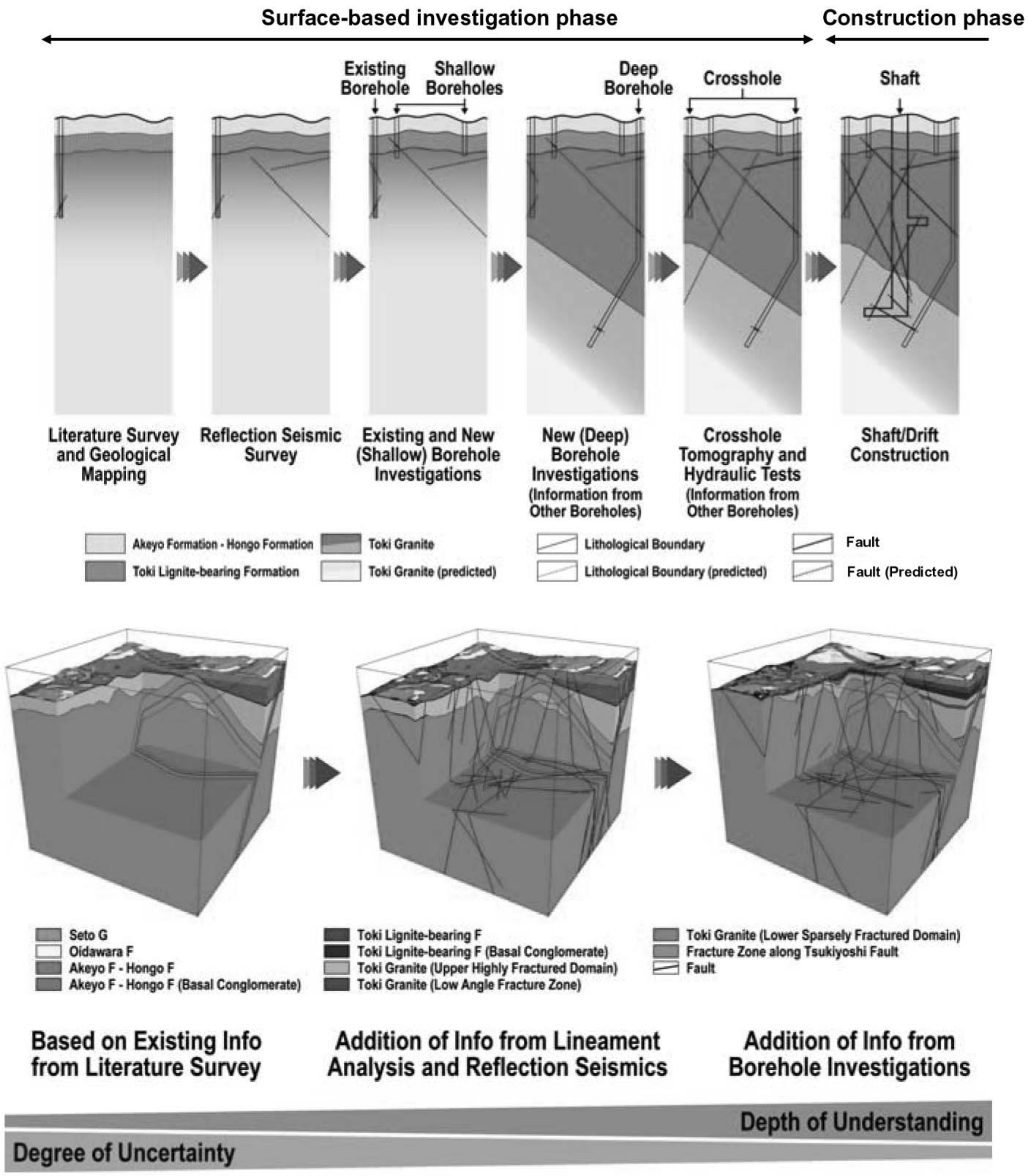


Fig. 8. Stepwise Investigations and Associated Improvement of the Geological Model for the Mizunami URL Site (after [41])

and monitoring technology for use deep underground, such as the Accurately Controlled Routinely Operated Signal System (ACROSS) (an approach applicable to reflection seismic and electromagnetic surveying) [42]. Such technologies will be put to practical use in the near future.

Such work undoubtedly represents a considerable effort to establish the toolkit and experience that NUMO will need for surface-based investigations at the PIA and DIA stages. The extent to which it can be directly applied will, however, depend critically on the characteristics of the volunteers selected as PIAs. This will be especially challenging due to the short duration of PIA investigations and the fact that such characterisation may be carried out in parallel at several sites. NUMO is already working to develop outline site characterisation manuals, based both on this experience and that accumulated world-wide.

Although certainly very challenging, it is hoped that continuous optimisation of the site characterisation work will be facilitated by the NSA [24] and the supporting RMS tools [37].

3.2.3 Investigation in Underground Facilities

Underground facilities are increasingly seen as being essential for developing successful deep disposal projects. At early programme stages, generic URLs provide basic understanding of relevant deep environments, establish the tools necessary for their characterisation and serve as a link between conventional laboratory and natural analogue systems (see section 2.3.3.). Once a repository site is selected, a site-specific underground investigation facility may provide unique characterisation opportunities and allow data critical to licensing to be accumulated. Even at such a late phase, parallel operation of a generic URL may be desirable for carrying out support work, e.g. validation of improved investigation technologies. In any case, the construction of a site-specific underground investigation facility involves a considerable investment of funds and will be a focus of popular interest. It is important, therefore, that the technology for constructing and operating such a facility be well established beforehand.

In Japan, a small test area is being constructed in the site investigation area for an intermediate-depth repository at Rokkasho [43]. Future research and development conducted at the generic URLs will be aimed at enhancing the applicability and reliability of exploration technologies to relevant Japanese geological environments and tectonic settings. In the above-mentioned URL programmes, many characteristics of the underground geological environment will first be predicted in advance by models utilising best available data from phase 1. The validity of the model and the accuracy of quantitative predictions will then be evaluated during phases 2 and 3 by comparison with direct underground observations. This should allow direct feedback to help focus NUMO's siting work and to support the critical decisions to select PIAs, DIAs and, in particular, the final repository site.

3.3 Geosynthesis

Geological characterisation aims to provide a comprehensive and consistent overview of the geological environment at specific sites in terms of geology, hydrogeology, hydrochemistry, solute transport, rock mechanical and thermal properties, as required for repository design and safety assessment. The monitoring of perturbations to the geological environment, caused by natural events, e.g. seismic activity, and, at a later stage, by excavation of shafts and galleries, is also included here. A global integration methodology, which synthesises information from the wide diversity of specific investigation techniques, needs to be developed and demonstrated. In order to ensure transparency, a systematic approach is essential. This needs to be focused on the specified goals for the entire project, prioritised for each project phase - which takes into consideration interrelationships between experimental activities and practical requirements in terms of location, access, duration, etc.

In Japan, a basic site-specific geological analysis is ongoing along with a site investigation for the intermediate -depth repository at Rokkasho [43]. With the aim of establishing more comprehensive geological investigation techniques for the environments that may be considered for HLW, a "geosynthesis" methodology is being developed and tested at the JAEA URL sites. For this geosynthesis, objectives, layout and duration of individual investigations, e.g. on fractures, fracture zones, faults, etc., will be clearly defined and the process of analysing and integrating output to satisfy the needs of repository designers and PA modellers defined in advance. An example of such a framework (or flowchart) for geosynthesis is shown in Figure 9. The geosynthesis developed for the URL projects will be modified, based on accumulated experience, and optimised for application to the investigation of volunteer sites. This method could also be extended to apply to disposal of other waste types, including the intermediate-depth repository.

A further goal of the URL projects is to assess specific site characterisation methodologies within the framework of the geosynthesis. An iterative process of methodology and framework refinement should result in a cost-effective, quantitative model of the geological environment, which is tailored to the needs of both implementers and regulators. This process will be iterated with increasing detail in each phase of the URL projects, in order to build up experience and develop confidence in both the characterisation methodologies and the output of the geosynthesis.

3.4 Site-specific Design

3.4.1. Design Toolkit

Given a site with favourable conditions for geological disposal, appropriate repository design concepts need to be developed. At early stages of a programme, emphasis may be placed on rather idealised designs, which aim only to show basic feasibility of construction and the likelihood of meeting regulatory guidelines with regard to long-term, post-closure safety. As a project matures, with a special emphasis on maintaining local acceptance, other factors may play an increasingly important role in design - e.g. operational safety, QA, ease of understanding of the safety case by a non-technical audience, reversibility at early stages of implementation, cost (and resultant flexibility for providing local economic incentives), repository footprint, etc. The evolving designs need to be more rigorous and, in particular, explicit trade-offs may need to be made when conflicting requirements are placed on the system. In particular, the weighting of such conflicting requirements may be very site-specific.

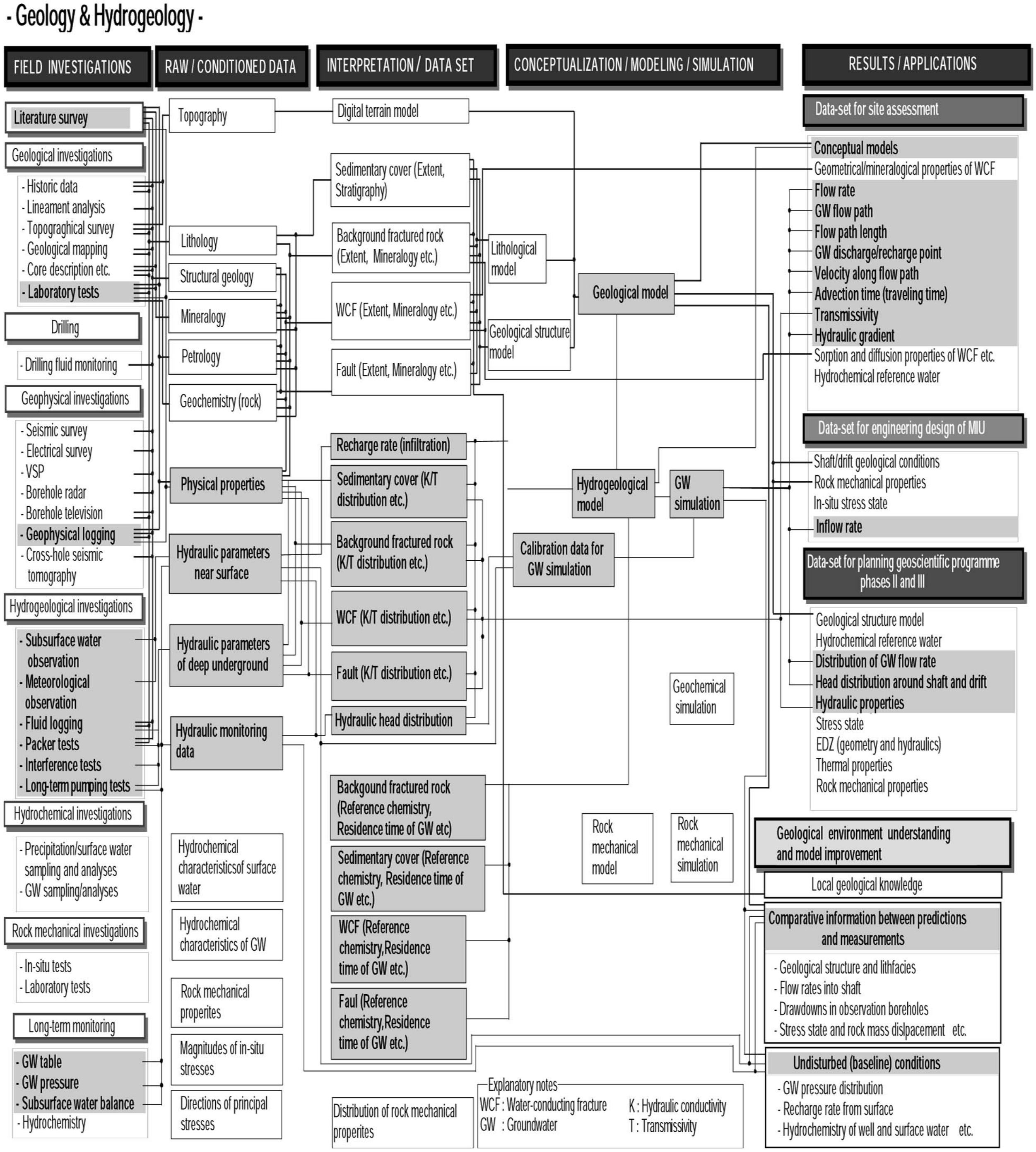


Fig. 9. Example of a "Geosynthesis" Systematic Framework for the Assessment of Geology and Associated Earth Science Input [44]

The challenge is not only the range of widely differing factors that needs to be considered when selecting between alternative design options (or when refining selected designs), but also the uncertainties that exist in most (or all) of the factors that need to be considered and the fact that some of these uncertainties will decrease with time, as the characteristics of the site become better defined. An important part of justifying any particular design (or justifying the selection of a particular disposal site) is a demonstration that potentially suitable alternatives have been considered and that the selected option represents, in some sense, "an optimum choice" or "better solution", taking into account a range of relevant factors (e.g. [45]).

For comparison of design options and/or sites, a multi -attribute (or multi-criteria) decision analysis (MAA) approach has been found to be useful and is being increasingly used by waste management organisations. To date, however, the attributes included often involve surrogates and the scoring models used are extremely simplistic – in many cases effectively representing expert opinion. Further development of this methodology may thus be justified.

In the Japanese intermediate-depth repository project, the extent of tailoring design to the site is a point of debate at present. Reference designs were developed in advance of detailed site investigation and there are currently plans to test them for the updated geological information derived from the underground facility [43]. The output from the JAEA URL projects, e.g. experience in site characterisation associated with underground construction, could provide support for such work.

For HLW, a structured approach for iterative development of repository concepts has been developed in Japan, which not only allows the repository design to be tailored to the site but also feeds back to allow optimisation of the characterisation programme [22]. This approach will also include development of top-level tools for information collation and synthesis, which will further allow prioritisation and optimisation of the associated R&D programme. The work involved will be fully documented, not only to provide a mechanism for QA via expert review, but also to inform key stakeholders of progress - with special emphasis on the local populations of the areas investigated.

Ideally, the output of such repository concept studies will be the definition of a range of potential designs / layouts for a number of different sites. If the number of sites / designs is impractically large, some form of MAA may be used to rank options at a top level. Because of the flexibility of the MAA software used, it is relatively easy to examine the effects of the changing the weighting of different attributes (e.g. "public acceptance" or "cost") in order to reflect the concerns of different stakeholder groups. Ideally, stakeholders could take part directly in such concept and site comparison exercises. Initially, plans exist to involve key stakeholders – and in particular local communities – in the process of defining some of the attributes to be considered and their associated weightings.

At a more technical level, optimisation may involve balancing competing requirements on a site-specific basis. As an example, consider tunnel layout - which could be optimised with respect to:

- stress field, for construction engineers;
- hydraulic gradient, for post-closure safety assessors;
- access routes, for operational logistics;
- surface footprint, for public acceptance;
- construction effort, to minimise costs;
- etc.

Decision-making within such technical optimisation would be guided by the envisaged RMS.

3.4.2 Designing for Robustness

In order to minimise vulnerability to uncertainties, repository designs should, as far as practical, be robust. Robust systems are characterised by simple, well understood or easily characterised features and phenomena and an absence of, or insensitivity to, detrimental phenomena [46, 47]. This could, for example, involve designs and materials that are known to be resilient to a broader range of conditions than expected, providing a large margin of safety. The design strategy should aim to develop a predictable and robust system based on specific site information. As the information base on the site may be built up only gradually and requirements / constraints on design may change depending on the progress of a disposal programme, a flexible repository design strategy is also required, which includes regular iteration with geological characterisation (geosynthesis), PA and public communication groups.

To date, evaluation of robustness, especially for expected scenarios, has focused on sensitivity analysis associated with safety assessments – which is useful in identifying the key factors which determine the margin of long-term safety. This is complemented by examining "what if?" scenarios, which lie outside the range expected on the basis of scientific evidence, but help to define worst-case perturbations. Nevertheless, this ignores the potentially more critical area of ensuring robustness in terms of operational safety - which could be a major challenge for the future.

In the Japanese intermediate-depth repository project, so far there has been only limited evaluation of post-closure robustness and associated development of a robust safety case for construction and operation [43]. Depending on requirements for licensing (which are under discussion by the NSC), this is an area that could be a priority in the near future.

For HLW, the generic H12 disposal system was designed with robustness of post-closure safety in mind, to ensure its applicability to a wide range of potential siting environments in Japan. This may, however, need further consideration depending on the sites considered – e.g. a coastal site may be subject to a range of specific scenarios which were not fully considered in H12. Operational safety has been identified as a priority area and effort is ongoing to examine the operational hazards associated with waste emplacement (based on tele-operated technology) and to develop a list of potentially significant disruptive scenarios. Such effort can be used as the basis for carrying out equivalent work for geological disposal of other types of waste in the future.

4. CHALLENGES IN THE MANAGEMENT AND COORDINATION OF R&D

4.1 Challenges from an Exponentially Expanding Knowledge Base

4.1.1 Knowledge and Knowledge Management: Definitions

In this particular case, "knowledge" is taken to be a 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 – e.g. geology, chemistry, materials science, civil engineering, etc.), generic waste management knowledge and project-specific knowledge.

The term "Knowledge Management" as used here covers all aspects of the development, integration, QA, communication and maintenance/archiving of knowledge – including data, understanding and experience. It is an active process, which is focused by specific programme or project requirements (themselves developed and structured by an RMS). Knowledge is not static, but evolves with time in line with general progress in science and technology. 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 before older staff members retire.

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.

Knowledge Management is a term commonly used in many areas of technology but, in general, focus is on conventional approaches to systematic handling of technical information. For Japanese waste management, however, this has been seen to be an area where a major paradigm shift is urgently needed to meet future challenges [48].

4.1.2 Definition of the Problem

In the '80s, or even in the '90s, it was possible for top managers in the nuclear waste field to have a reasonably comprehensive overview of all relevant technical work contributing to a repository project. Since then, there has not only been breathtaking growth in basic knowledge, but work has become more international and has been opened up to wider scrutiny – with increasing emphasis on non-technical aspects associated with open communication and public acceptance. Except possibly in the smallest and most isolated programmes, this is beginning to lead to an obvious loss of overview, synthesis and flexibility.

In Japan, the information explosion has been observed, in particular, in R&D areas supporting the HLW disposal programme. First evidence of this problem emerged during the H12 project [21, 25-27], which was the second generic study to demonstrate technical feasibility of safe disposal of HLW waste. One of the greatest difficulties experienced was integrating the huge amount of information / data on geological environments, engineering and safety assessment. The total size of the main H12 reports was ~ 2,000 pages, which can be contrasted with the ~ 400 pages of the first "H3" study [49], produced only 9 years earlier. Work has continued since H12 to increase technical reliability and confidence in the safety of geological disposal. Additional data/information as of 2005 has been summarised in the ~1,000 pages of the H17 progress report [40, 50-51].

An example of the increase in data important for design and safety assessment of the repository between H12 and H17 is presented in Table 2. Note that individual data points are further associated with a considerable quantity of supporting information, e.g. on experimental conditions for acquisition, providers, uncertainty, quality assurance, degree of reliability, etc. The amount of such information will continually increase in the future.

Table 2. Increase in the Number of Key Data for Repository Design and Safety Assessment (after [48])

Data	H12	H17
Thermodynamic database	383	425
Kd values for buffer/rocks	19,825	21,061
De for buffer/rocks	648	1,424
Buffer properties (thermal, hydraulic, mechanical, chemical, etc)	1,328	1,818
Steel corrosion data (incl. NAs)	~ 1,800	~ 2,640

N.B. Kd: distribution coefficient; De: effective diffusivity; NA : natural analogue

In addition to raw data, expansion of knowledge also includes information derived by application of advanced investigation techniques for geological environments - for example 3D digital geological models and multi-spectral satellite images. Figure 10 gives an example of a 3D digital model and corresponding geological map developed for the Mizunami URL site [52]. The 3D digital map has been used directly to generate a 3D hydrogeological model using associated data on hydraulic conductivity, which has further expanded the information to be managed. Groundwater flow simulation can be carried out for the 3D hydrogeological model to identify dominant flow paths, which in turn are used for radionuclide migration calculations. Furthermore, as site investigation proceeds, additional data and information will be provided to improve the model. All stages of this iterative process should be fully recorded to ensure traceability.

When the total supporting information base for the HLW project is expressed as bytes of data, it is already in the Terabyte range and is expanding exponentially – roughly in line with "Moore's Law" on expansion of computing speeds and data storage capacities. An innovative approach is thus needed for its management – going beyond the traditional dependence on librarians to collate data and expert "gurus" to synthesise it. This is driven by the HLW programme, but the approach and, indeed, much of the information contained will be directly applicable to repositories for other types of waste.

4.1.3 Structure of the Knowledge Base

All programmes possess some kind of structured knowledge base. In most cases, however, this is based on conventional bibliographic classification schemes, which involve sub-dividing work by technical discipline, sub-discipline, etc. Information handling also uses conventional approaches for cross-referencing, quality assuring and collating of this material.

In Japan, it is planned to structure existing knowledge on the basis of the requirements specified by end-users. Ideally, this would interface directly to a formal RMS, of the type previously discussed in section 3.1.1. Although requirements management is recognised to be essential by the Japanese HLW implementing organisation and formal systems are under development [24, 37], these are not yet operational. To initiate work in the absence of clearly defined requirements, a prototype knowledge base will therefore follow the structure of a geological repository safety case, which will certainly be a key requirement for all implementers [34] and will need to be evaluated by regulators.

The various components of the knowledge base are listed in Table 3 along with concepts for their management, identification of some of the key developments needed to move to the "next generation" Knowledge Management System (KMS) (see below) and associated comments on implementation [48].

DATA: Data management is, in some ways, the most fundamental component of the knowledge base, although a distinction is made between raw data (internal), external solicited data and processed data. Raw data would include the experimental laboratory measurements used to derive the type of design and safety assessment data listed in Table 2 and also the basic geological data used to derive the figures illustrated in Figure 9. All such data should be subject to defined QA procedures.

DOCUMENTS: All data will be associated with supporting documentation. The technology already exists to catalogue, cross-reference and archive documents electronically. Two major challenges for the future, however, are automation of the QA of documents and ensuring robust archiving of electronic information.

SOFTWARE: For the case of software, the issues are broadly similar to those considered for documents, with

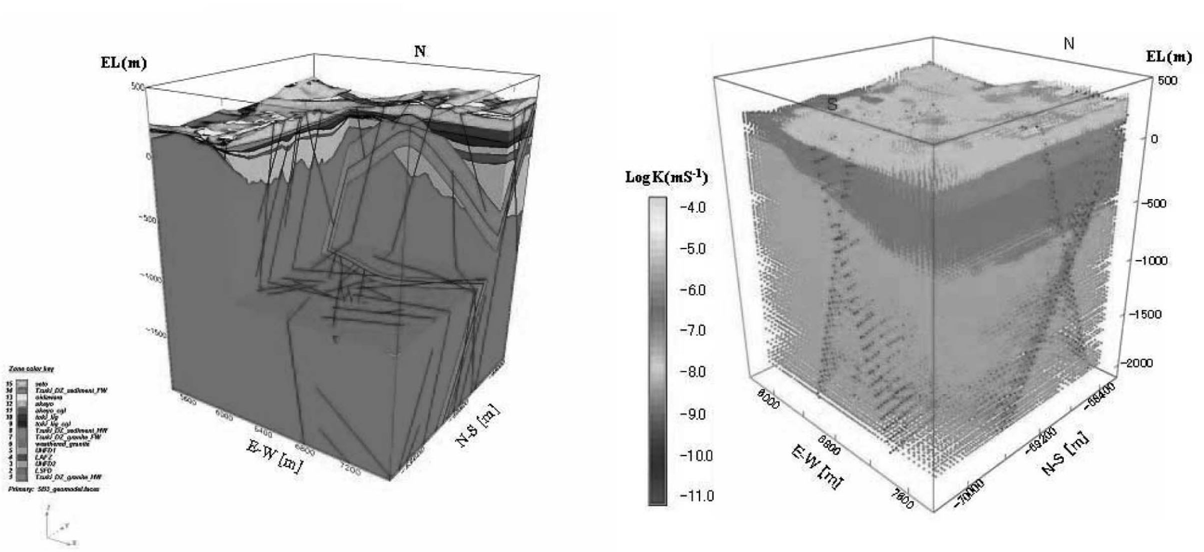


Fig. 10. Example of a 3D Geological Model and Hydrogeological Model Developed for the Mizunami URL Site

possibly even more serious problems associated with QA and archiving in forms which will be readable in the future.

EXPERIENCE and METHODOLOGY: Experience and associated practical methodology can be managed, to some extent, by ensuring comprehensive documentation of all relevant procedures, but this can cover only a fraction of the tacit experience represented by an expert workforce. A well planned and structured training programme is an essential component of managing such knowledge. In the future, however, this might be complemented by specially designed expert systems conditioned by the accumulated experience of retiring staff members.

SYNTHESIS: The higher levels of the hierarchy of the knowledge base are inherently more difficult to automate – although the developments suggested above for the lower levels may free more time for qualified staff to concentrate on this critical level. Important here is the multi-disciplinary overview experience required to integrate the multiple sources of information needed for processes such as total system performance assessment. Expert systems could, conceivably, help to some extent – but this would need technology significantly more advanced than that presently available.

GUIDANCE: Top-level coordination and, in particular, providing guidance to knowledge producers on future requirements is even more challenging. A particular key area, which falls beyond any electronic system, is the anticipation of future developments – both technical and socio-political – which can have a major influence on user requirements and the knowledge needed to satisfy them. To address this gap, a system of "Think Tanks" is being considered, based on the experience in other advanced industries that have had to address the same problem.

PRESENTATION: Knowledge presentation to the wide range of users must be seen as a key development area – having a lot of knowledge is not of much value if it cannot be easily accessed. Maintaining state-of-the-art capacity in graphical presentation of complex information and other user-friendly interfacing methods is thus clearly a high priority.

Table 3. Components of the Knowledge Base (after [48])

Form of knowledge	Management functions	Content	Required developments	Comments
Data	Data management	- raw data (internal) - solicited data (external) - processed data	- autonomic QA - internal & external data mining - autonomic data processing	Potential area for international collaboration
Documents	Document management	- internal documents - key external documents	- robust archive - autonomic QA / cataloguing / cross-referencing	Electronic archiving critical problem area
Software	Software management	- archive of all relevant codes / databases - archive of manuals & handbooks - archive of relevant output	- robust archive - autonomic change management - formal approaches for QA	Electronic archiving critical problem area
Experience & methodology	Resource management	- procedure manuals & guidebooks - expert systems - training materials	- use of expert systems to preserve experience - training approach for the next generation	Much of requirements could be addressed by national (regional?) training centre
Synthesis	Knowledge integration	- experienced synthesis team - expert systems	- description of key integration processes - approach to QA	Needs considerable development to automate
Guidance	Knowledge coordination	- experienced coordination team	- prediction of requirements (Think Tank) - process for filling key gaps in knowledge	Very difficult to automate
Presentation	User / producer dialogue	- user friendly interfaces (interactive – allowing dialogue)	- high-end graphical methods for presenting complex information	Should be tailored to needs of different stakeholders

4.1.4 Next Generation KMS

The development of a conceptual Knowledge Management System (KMS) is challenging in itself. Based on the considerations above, however, to be of real use this should not simply be a passive tool to archive and disseminate information. It requires internal analytical facilities to synthesise and integrate material from a diversity of sources, identify trends and inconsistencies and, ideally, even produce feedback to the data producers. In effect, it should replace many of the functions of the network of peer reviewers and expert advisors who currently carry out such work.

A further problem lies with establishing a strategy to produce a functioning system which has the capacity to respond to a rapidly growing knowledge base, the flexibility to respond to changing requirements of end-users and has the user-friendliness to ensure that it is adopted by both knowledge-producers and knowledge-users.

Such challenges have, in the past, prevented any active initiative to implement the “next generation” KMS. In Japan, it is considered that, with the dramatic strides in relevant areas such as expert systems, artificial intelligence, neural networks, web-based agents and bots, etc., the time seems ripe to re-investigate this option. When particular emphasis is placed on advanced electronic information management approaches, the situation looks more feasible:

- Already, most key information for repository projects is available electronically and accessible via internet / intranet systems. It is reasonable to expect that this will very soon provide effectively 100% coverage;
- Increasingly sophisticated content-recognition/cross-referencing systems allow relationships between documents and any form of datasets to be defined in much more detail than traditional document labelling/keyword approaches;
- The development of autonomic data mining techniques involving network agents, bots, etc. is currently an area of very rapid progress, which allows much of the information gathering, sorting and compilation processes to be automated;
- The combination of expert systems with autonomic learning approaches (e.g. based on neural networks) allows, at least in principle, many of the key processes involved in knowledge management – collation, synthesis, review, etc. – to be completely automated.

The preliminary concept for the Japanese KMS is shown in Figure 11. Although such a system is still at the early stages of internal discussion, it can be seen that the emphasis is on interaction – with two-way flows between the knowledge base and the central guiding knowledge office, the R&D sectors which produce focused new knowledge, the web which is the interface to the wider international community, the think tank which attempts to anticipate the inherently unpredictable future and, most importantly, the end-users – the sine qua non of the entire exercise!

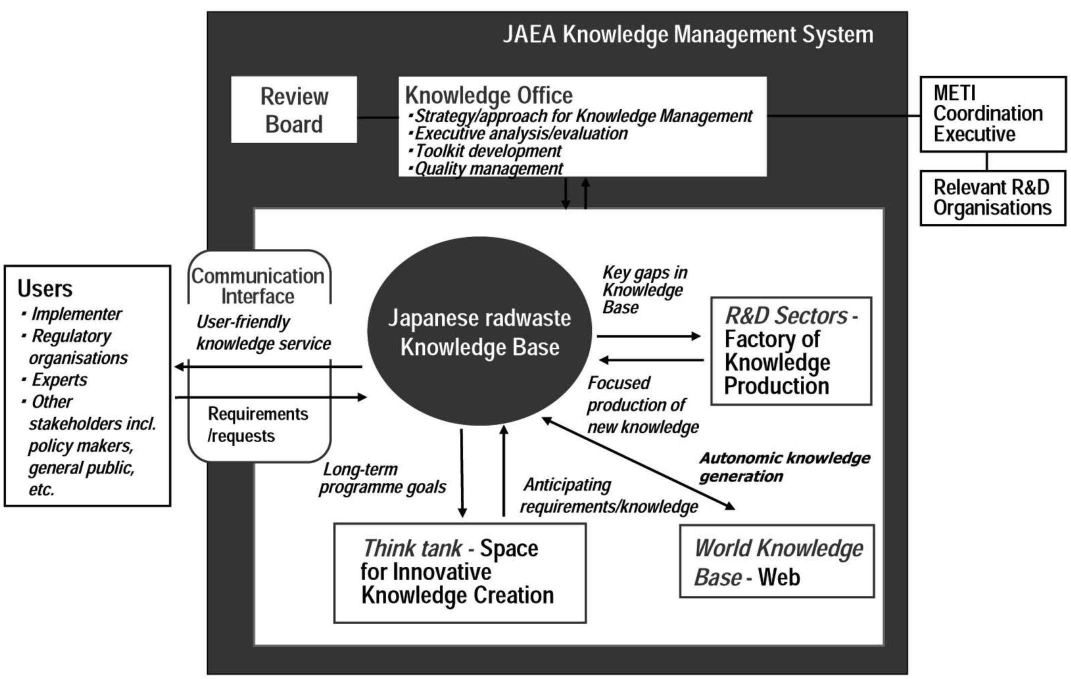


Fig. 11.Preliminary KMS Concept: Structure and Key Elements (after [48])

Table 4. List of Key Challenges in Future R&D

Topical area	Challenge	National / international
Improved inventories	- MIR & NORM wastes - Wastes from advanced reactors & reprocessing - Fusion power wastes - Feedback to optimise production - Integrated evaluation toolkit	N N/I I N/I N
Repository concept development	- Flexible design process which evolves with system understanding - Advance R&D to evaluate potential optimisation approaches and ensure that implementation technology is available when needed	N/I N/I
- Safety	- Post-closure: Models & databases to provide more realism and interfaces to improve communication to a wider range of stakeholders (HLW & TRU) (see Safety Assessment) - Assessment of representative long-term scenarios for other L/ILW - Operational: rigorous assessment for underground operations	N/I N N/I
- Practicality	- Ensuring quality-assured emplacement of HLW EBS by remote handling - Extend work for geological disposal of ILW / TRU	N N/I
- Acceptability	- Evaluate constraints on enhanced monitoring & retrieval - Check safety of CARE concept	N/I N/I
Safety assessment	- Next generation, more realistic approach - Time dependent scenarios (esp. tectonics, coastal sites) - PA synthesis structures	N/I N/I N
- Near-field	- Representation of geometry & time-dependent interaction of all EBS components (HLW, extended to other waste)	N/I
- Geosphere	- More realistic models including time-dependency (e.g. high pH plume)	N/I
- Biosphere	- More realistic models (e.g. GBI) including time-dependency	N
- Verification & Validation	- Verification & Validation / QA methodology for key models (esp. time variation) - New analogue projects focused on validation	N/I I
Stakeholders confidence	- Technology for improving communication of technical issues and establishing dialogue	N/I
Implementation and regulatory formulation support	- Structured approach & requirements management - Anticipating regulatory requirements	N N
Site Characterisation toolkit	- Proven tools & methodology for implementing stepwise site characterisation methodology / technology - Geosynthesis methodology	N N
Design toolkit	- Methodology for tailoring designs to sites and prioritising options (MAA/RMS) - Operational safety robustness: assessment for expected & perturbation scenarios	N/I N/I
KMS	- Next generation KMS - School & specialist projects to attract and train future generations of staff	N/I N/I

4.2 Manpower Logistics and Training

The difficulty of assuring future manpower requirements is a general problem in the nuclear industry. In the nuclear waste business, in particular, the situation is particularly critical due to the general lack of established training in this complex, multi-disciplinary area. Many of the older national programmes have the additional problem of the loss of institutional knowledge, as the generation who developed original concepts approaches retirement.

In terms of manpower, it is clear that the envisaged HLW repository project will require significant numbers of widely experienced staff – particularly as field operations may run in parallel at different sites. This is complicated as repository programmes for other wastes are moving into an active planning stage. The LLW intermediate-depth and HLW deep geological repository projects will both be first-of-kind facilities 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 integrated studies in URLs. Experience or "tacit knowledge" can be transferred to younger generations by collaboration with older, experienced staff in such work.

To attract highly qualified staff, the R&D work involved should be seen to be attractive – interesting, exciting, state-of-the-art; this presents not only a technical challenge in devising such projects, but also a communication challenge to younger generations. 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.

Finally, focused, specialist training facilities will be needed. As yet, the only major initiative of this type is the ITC, which is an international training centre based in Switzerland [53]. Given the specific requirements of the Japanese programme, possibilities to build on the base provided by the ITC and establish a Japanese Regional Training Centre are being investigated. Like the ITC, this would be based at a location where underground research facilities are available for training in this key area. It might additionally maximise synergies by offering training for other East Asian countries, which are likely to have very similar needs.

5. OVERVIEW AND CONCLUSIONS

Some of the key challenges identified in this overview are summarised in Table 4. As indicated, many of these are potentially suitable topics for international collaborative projects. Given that resources are limited and the technical challenges are great, enhanced international collaboration can be expected to be a feature of national programmes in the 21st century. Although work in the past has tended to focus on technical topics, the more fundamental aspects of developing a next generation KMS and attracting and training key staff may be worth particular emphasis. Regardless of how good technical infrastructure is, projects are doomed to failure if they are incapable of managing the information that they generate or do not have the expert staff needed to use the output of the KMS in order to implement a successful programme.

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REFERENCES

[1] http://www.jaea.go.jp/04/turuga/tief5/images/TIEF5-S1_2E.pdf
[2] C. McCombie and N. Chapman, Multinational and Regional Disposal Initiatives: Nearing a Turning Point, Proc. 11th International High-Level Radioactive Waste Management Conference, April 30 – May 4, 2006, Las Vegas, NV, USA, pp.1158-1163 (2006).
[3] S. Saito, Speech in the plenary session of 2006 International Congress on Advances in Nuclear Power Plants (ICAPP '06) (2006) (http://aec.jst.go.jp/jicst/NC/eng/speeches.htm).
[4] http://www.iaea.org/Publications/Documents/Infcircs/ 1997/infcirc546.pdf, e.g. p.29.
[5] AEC, Framework for Nuclear Energy Policy (Tentative Translation), Japan Atomic Energy Commission, October 11, 2005 (2005).
[6] A. G. Croff, ORIGEN2 – A Revised and Updated Version of the Oak Ridge Isotope Generation and Depletion Code, Oak Ridge National Laboratory, ORNL-5621 (1980).
[7] ENEA, Inventario Nazionale dei Rifiuti Radioattivi - 2000, ENEA, Rome, Italy (2000).
[8] P. Riggar and C. Johansson, Project Safe, Low and Intermediate Level Waste in SFR-1, Reference Waste Inventory, SKB Technical Report TR-01-03, SKB, Stockholm, Sweden (2001).
[9] USDOE, Summary Data on the Radioactive Waste, Spent Nuclear Fuel, and Contaminated Media Managed by the US Department of Energy. USDOE Office for Environmental Management, USDOE, Washington DC, USA (2001).
[10] Nirex, The 2001 United Kingdom Radioactive Waste Inventory, Nirex Reports N/041 to N/048, Nirex, Harwell, UK (2002).
[11] D. F. McGinnes, Model Radioactive Waste Inventory for Reprocessing Waste and Spent Fuel, Nagra Technical Report NTB 01-01, Nagra, Wettingen, Switzerland (2002).
[12] FEPC and JNC (2000), Progress Report on Disposal Concept for TRU Waste in Japan, JNC TY1400 2000-002 TRU TR-2000-02.

[13] FEPC and JAEA, Second Progress Report on Research and Development for TRU Waste Disposal in Japan -Design, Safety Assessment and Means of Implementation in the Generic Phase-, (2006) (English version in preparation).
[14] I. G. McKinley, H. Kawamura, F. Neall and K. Ando, Repository Design Optimisation for Long-lived ILW, Sci. Basis Nucl. Waste Manag., XXIV, pp.843-850 (2001).
[15] S. Masuda, H. Umeki, I. G. McKinley and H. Kawamura, Management with CARE, Nuclear Engineering International, 49 (604), pp.26-29 (2004).
[16] Nagra, Project Opalinus Clay – Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis), Nagra Technical Report, NTB 02-05, Nagra, Wettingen, Switzerland (2002).
[17] I. G. McKinley, F. B. Neall, H. Kawamura and H. Umeki, Geochemical optimisation of a disposal system for high-level radioactive waste, J. Geochem. Exploration, 90, 1-8 (2006).
[18] National Report of Japan for the Second Review Meeting, Joint Convention on the Safety of Spent Fuel Management, pp.B-9, (2005).
[19] H. Umeki, S. Masuda, I. G. McKinley: Advanced Repository Concepts Required for a Volunteering Approach to Site Selection, GLOBAL 2003, A topical meeting embedded within the ANS/ENS International Winter Meeting, pp.262 -267, 16-20 November 2003, New Orleans, USA (2003).
[20] UK EA, The Environment Agency's Assessment of BNFL's 2002 Environmental Safety Cases for the Low-Level Radioactive Waste Repository at Drigg, UK Environment Agency, NWAT/Drigg/05/001 (Version: 1.0) (2005).
[21] JNC, H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, Project Overview Report, Second Progress Report on Research and Development for the Geological Disposal of HLW in Japan, JNC TN1410 2000-001 (2000).
[22] NUMO, Development of Repository Concepts for Volunteer Siting Environments, NUMO Technical Report TR-04-03, NUMO, Tokyo, Japan (2004).
[23] OECD/NEA, Engineered Barrier Systems (EBS): Design Requirements and Constraints, Workshop Proceedings, Turku, Finland, 26-29 August 2003, OECD/Nuclear Energy Agency ISBN 92-64-02068-3, Paris France (2004).
[24] K. Kitayama, H. Umeki, H. Ueda, I. G. McKinley and K. Kaku: A Structured Approach for Stepwise Tailoring of Repository Concepts to Volunteer Sites, Proc. 10th Int. Conf. Environmental and Radioactive Waste Management, ICEM'05, Glasgow, Scotland (2006).
[25] JNC, H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, Supporting Report 1: Geological Environment in Japan, Japan Nuclear Cycle Development Institute, JNC TN1410 2000-002 (2000).
[26] JNC, H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, Supporting Report 2: Repository Design and Engineering Technology, Japan Nuclear Cycle Development Institute, JNC TN1410 2000-003 (2000).
[27] JNC, H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, Supporting Report 3: Safety Assessment of the Geological Disposal System, Japan Nuclear Cycle Development Institute, JNC TN1410 2000-004 (2000).
[28] R. Metcalfe and C. Walker, Proceedings of the International Workshop on Bentonite-Cement Interaction in Repository Environments, 14-16 April 2004, Tokyo, Japan, NUMO-TR-04-05, NUMO (2004).
[29] M. Toyota and I. G. McKinley, Optimization of the Engineered Barrier System, Proc. 8th International High-Level Radioactive Waste Management Conference, May 11-14, 1998, Las Vegas, NV, USA, pp. 648-652 (1998).
[30] M. J. Apted, A Modest Proposal: A Robust, Cost-Effective Design for High-Level Waste Packages, Materials Research Society Symp. Proc. Vol.506, pp. 589-596, (1998).
[31] E. Lindgren, S. Pettersson and J.-P. Salo, R&D program for Horizontal Emplacement KBS-3H, Proc. of 10th International High-Level Radioactive Waste Management Conference (IHLRWM 2003), pp.571 - 577, 30 March - 2 April 2003, Las Vegas NV USA (2003).
[32] S. Masuda, H. Kawamura, I. G. McKinley, F. Neall and H. Umeki, Optimising repository design for the CARE concept, 11th International High-Level Radioactive Waste Management Conference, April 30 – May 4, 2006, Las Vegas, NV, USA, pp.507-514 (2006).
[33] K. Ishiguro, H. Ueda, K. Wakasugi, Y. Sakabe, K. Kitayama, H. Umeki and H. Takase, "EBS Modelling for the Development of Repository Concepts Tailored to Siting Environments", in the Proceedings of the NEA Workshop on "Integration of Engineered Barrier Systems in the Safety Case : The Role of Modelling", La Coruna, Spain, 24-26 August 2005, OECD/Nuclear Energy Agency (to be published).
[34] JNC, H17: Development and management of the technical knowledge base for the geological disposal of HLW - Knowledge Management Report -, Japan Nuclear Cycle Development Institute, JNC TN1400 2005-022 (2005).
[35] W. Miller, R. Alexander, N. Chapman, I. McKinley and J. Smellie, Geological disposal of radioactive wastes and natural analogues: lessons from nature and archaeology. Waste Management Series 2, Pergamon, Amsterdam (2000).
[36] NUMO: Evaluating site suitability for a HLW repository, NUMO Technical Report TR-04-04, NUMO, Tokyo, Japan (2004).
[37] Y. Sakabe, H. Ueda, K. Ishigro, K. Kitayama, McKinley, I. G., and K. Kaku, Implementation of a requirements management system for the Japanese HLW programme, Proc. IAEA International Conference on the Safety of Radioactive Waste Disposal, Tokyo (2005).
[38] Nuclear Safety Commission of Japan, Commonly Important Issues for the Safety Regulations of Radioactive Waste Disposal (2004).
[39] Nuclear Safety Commission of Japan: Focused Research Programs on the Nuclear Safety (2004) (in Japanese).
[40] JNC, H17: Development and management of the technical knowledge base for the geological disposal of HLW, Supporting Report 1: Geoscience study, Japan Nuclear Cycle Development Institute, JNC TN1400 2005-014 (2005) (in Japanese).
[41] S. Takeda, Current Status of R&D Activities at Tono Geoscience Center - Mizunami Underground Research Laboratory Project and Regional Hydrogeological Study Project -, Proc. Int. Conf. JNC Underground Research Laboratory Projects in Mizunami (ICGM'04), Part 1,, October 21, Mizunami, Japan, JNC TN7400 2004-010, pp.65-82 (2004).
[42] R. Tsukui, T. Niizato, K. Aoki and T. Fukushima, Developing

a Remote Monitoring System Using ACROSS in Horonobe Underground Research Laboratory, Proc. 1st International Workshop on Active Monitoring in the Solid Earth Geophysics (IWAM04), Task Group for Active Monitoring, Mizunami, Japan, pp.30-35 (2004).
[43] A. Yamato, The current status of JNFL sub-surface disposal plan for relatively higher LLW, IAEA International Conference on the Safety of Radioactive Waste Disposal, Tokyo, Japan, 3-7 October 2005, Contributed Papers, IAEA-CN-138/39, pp.153-156 (2005).
[44] H. Saegusa, A. Sawada, K. Inaba, S. Takeuchi and K. Nakano, A Study of Uncertainties in Groundwater Flow Evaluation Using Multiple Modeling Approaches, JNC Technical Review, No. 20, pp. 75-89, JNC TN1340 2003-002 (2003) (in Japanese).
[45] J. Bel, C. De Bock and J-P. Boyazis, Comparing Technical Concepts for Disposal of Belgian Vitrified HLW, Proc. of Workshop on Engineered Barrier Systems (EBS): Design Requirements and Constraints, OECD/NEA Report No. 4548, pp.87-99, OECD/NEA, Paris, France (2004).
[46] NEA, Confidence in the Long-term Safety of Deep Geological Repositories, Its Development and Communication, OECD/NEA, Paris, France (1999).
[47] NEA, Establishing and Communicating Confidence in the Safety of Deep Geologic Disposal, OECD/NEA, Paris, France (2002).
[48] T. Kawata, H. Umeki and I. G. McKinley, Knowledge Management: Emperor's New Clothes?, Proc. 11th International High-Level Radioactive Waste Management Conference 2006, Las Vegas, Nevada, April 30-May 4, 2006, pp.1236 -1243 (2006).
[49] PNC, Research and development on geological disposal of high-level radioactive waste, First Progress Report - H3, Power Reactor and Nuclear Fuel Development Corporation, PNC TN1410 93-059 (1992).
[50] JNC, H17: Development and management of the technical knowledge base for the geological disposal of HLW, Supporting Report 2: Repository engineering technology, Japan Nuclear Cycle Development Institute, JNC TN1400 2005-015 (2005) (in Japanese).
[51] JNC, H17: Development and management of the technical knowledge base for the geological disposal of HLW, Supporting Report 3: Safety assessment method, Japan Nuclear Cycle Development Institute, JNC TN1400 2005-016 (2005) (in Japanese).
[52] H. Saegusa, M. J. White, P. Robinson and J. Guimerà, Development of a System for Integrated Geological Modelling and Groundwater Flow Simulation, Proc 11th International High-Level Radioactive Waste Management Conference, April 30 – May 4, 2006, Las Vegas, NV, USA, pp.330-337 (2006).
[53] http://www.itc-school.org/