High-level radioactive waste management: R&D challenges for the 21st century

Ian G. Mc Kinley

Nagra, Wettingen, Switzerland

Background

During the latter half of the 20th century, major progress was evident in the development of deep geological disposal concepts for high-level radioactive waste (HLW). There is now a broad consensus that safe disposal is possible in a wide range of different geological settings, with the required isolation being assured by various combinations of natural and engineered barriers. Despite large investments in supporting R&D, however, progress towards implementation of repositories has been generally much slower than originally planned in national programmes (with the notable exception of Finland). The factor contributing most to such delays has been the growth of public opposition to these (and, indeed, most other major industrial) projects.

In Japan, the technical foundations for geological disposal of HLW were documented by the H3 (PNC, 1992) and H12 (JNC, 2000) projects. The associated generic safety assessments illustrated the fundamental feasibility of siting a repository in the Japanese archipelago, with a particular emphasis on post-closure safety. Based on this assurance, when NUMO was established as the HLW disposal implementing organisation, they were able to adopt a novel "volunteering" approach to siting, which acknowledged the great importance of acceptance – particularly by local communities.

In its few years of existence, NUMO has made remarkable progress in establishing itself as a key player in the international radwaste business. Unfortunately, they have yet to find volunteers. Nevertheless, NUMO's documented approaches to characterising (and comparing) sites (NUMO, 2004a) and developing appropriate repository concepts (NUMO, 2004b) allow some of the main R&D challenges for the next 3 to 5 decades (or even longer) to be identified.

A missing part of the entire Japanese waste management jigsaw, however, is the "HLW Regulator". International experience has indicated that progress is facilitated by a strong regulatory organisation which is seen to be independent and technically competent and is capable of producing clear regulations (and associated compliance guidelines) which embody a commitment to facilitating implementation of suitable repository projects. The regulator will have additional R&D requirements focused on its own particular role but, like NUMO, may also want to establish higher profile "flagship" projects as part of establishing credibility - a very challenging task for a new organisation in this complex, multi-disciplinary field.

Site characterisation

NUMO has defined a stepwise site selection procedure following the Final Disposal Act, which commences with literature studies of volunteers to identify suitable Preliminary Investigation Areas (PIAs). A number of PIAs are investigated in parallel, using surface-based techniques including deep boreholes. Thereafter, one or more Detailed Investigation Areas (DIAs) are selected for more intensive characterisation – including studies from an underground research facility. This leads to selection (or confirmation) of the site for repository implementation, although site characterisation activities would continue throughout the entire construction and operation phases.

The data collection, synthesis and interpretation procedure has to be tailored to the particular volunteer sites, which could be very different in terms of geology, geography and accessibility. NUMO is committed to carrying out such work in an open and transparent manner. This should result in all decisions with respect to siting being fully traceable, based on quality-assured information.

Special challenges resulting from the chosen procedure include the requirement to study several sites in parallel and the expected need to show that level of investigation is “equivalent” for all sites. If only one or two suitable volunteers come forward and they are reasonably similar, this may not be a serious problem. For a larger number (3 or more), this could become extremely difficult – particularly if they differ considerably in terms of geological & tectonic setting, host rock, etc. This potential problem has already been identified by NUMO and efforts are underway to develop a formalised approach to defining the flow of information from the raw field data to the interpreted characteristics required for repository design and safety assessment (SA). The extent to which this can be done on a generic basis is, however, limited – especially because of the inherent flexibility in design (see below) which means that there needs to be iterative development of the site characterisation plan, the reference design and the associated SA. Given that all NUMO’s work will be carried out on “real sites”, under close public inspection, the importance of a well-integrated – and safe – characterisation programme cannot be overemphasised.

These basic difficulties are made worse by the very tight schedule set for the characterisation work. It should be emphasised that the time between formation of NUMO and selection of DIAs is just over a decade on the basis of current planning. In Finland the equivalent time period was over twice as long and this period will be probably four to five decades (or even longer) in Sweden, Switzerland, the UK, etc. This short time allows for very little opportunity to “learn as you go”. The equipment and methodologies used thus need to be reasonably well established in advance and, equally importantly, the project teams involved must be experienced in their application. It is noticeable that the experienced teams in other national programmes gained their background during decades of continuous field work. Even though often characterised by extensive “teething problems” during early stages of work, the continuity of key staff allowed the programmes to evolve with improvements of efficiency and technical sophistication. The experience gained in the JNC field programmes at the Mizunami and Horonobe sites can certainly contribute greatly here, especially if they can be scheduled to provide tools, experience and manpower as and when required for the PIA and DIA investigations.

It is presently unclear what role the regulator will play in the site characterisation process. This varies considerably in other national programmes – in some cases being very active (e.g. reviewing field investigation programmes and resulting raw data) and in others much more passive (e.g. reviewing only final top-level “geosynthesis” documentation). In either case, regulatory staff will also need the experience to assess the large quantities of complex data which result from site characterisation activities and be able to evaluate resulting decisions – particularly associated with the selection of PIAs, DIAs and, finally, the repository site. To aid both NUMO and the regulator, it is advantageous if a rigorous QA programme is implemented prior to initiation of data gathering (ideally with the explicit authorisation of both organisations). This will, of course, become even more critical at formal licensing stages.

Repository concept development

NUMO has a rather wide definition of the term “repository concept”, which includes not only the design of all surface and underground repository structures (tailored to a given siting environment) along with a description of how they would be constructed, operated and closed, but also an evaluation of operational and long-term safety and an assessment of socio-economic impacts. This is very much in line with recent international trends, which put increasing emphasis on site-specific tailoring of the rather simple concepts used originally for feasibility demonstration to improve operational practicality, robustness and safety. Much of such development has been driven by large-scale demonstration projects in underground test facilities, which have clearly illustrated the difference between a design that is *possible* to implement and one that is truly *practical* under the boundary conditions in a working repository.

When viewed from such a perspective, there are clearly a number of aspects of the H12 designs that need to be revised or, at least, analysed in further detail. These are mainly associated with the emplacement of the bentonite-based buffer, which plays many important roles in the associated safety case, e.g.:

- Colloid filter
- Hydraulic barrier
- Radionuclide sorption
- Plastic mechanical buffer
- Chemical buffer (esp. pH)

To guarantee that these roles are assured for relevant time periods, the buffer needs to be emplaced in a strictly quality assured manner and its mineralogical / structural stability must not be degraded by other engineered barrier materials under the expected hydrogeological and thermal conditions. Although a number of buffer emplacement methods were illustrated in H12, none have been demonstrated to meet defined quality levels (e.g. density, homogeneity) when implemented with appropriate tele-operated procedures. This could be particularly challenging in Japan, where potential host rocks are likely to be rather wet. Handling of highly compacted bentonite is known to be difficult under even high humidity conditions and its entire practicality / QA becomes questionable if significant liquid water is present. Nevertheless, there are certainly ways to engineer around this problem, such as the use of pre-fabricated EBS modules – a concept which was mentioned in H12 based on desk studies but, in the interim, is being increasingly studied based on experience gained in full-scale tests (e.g. SKB’s move from KBS-3(V) to the KBS-3H concept).

One other way of reducing the problems associated with water inflow involves the use of high quality tunnel (or borehole) liners. Indeed, the use of some form of liner may be required for mechanical stability / operational safety – as increasingly recognised internationally, even in programmes focusing on strong, hard rock. Unfortunately, designs of such liners tend to focus on use of concrete, which raises questions with regard to long-term degradation of bentonite. In fact, similar concerns arise from all uses of cementitious materials in repositories – including floors, plugs, seals, grouts, etc. As noted elsewhere (NUMO/Posiva, 2004), there are several possible approaches to solving (or avoiding) this problem:

- Remove the source of hyperalkaline fluids by
  - avoiding use of cement-based materials in sensitive areas
  - removal of any such materials before closure
  - adoption of “low pH” cements with suitable engineering properties
- Replace bentonite with a buffer material less sensitive to alteration by hyperalkaline fluids
- Add a barrier to prevent (or minimise) bentonite – cement interaction
- Develop models & databases to allow rigorous (and robust) quantification of the consequences of any bentonite alterations involved.

When considering this particular problem, a further characteristic of NUMO’s range of design options needs to be taken into account – the emphasis on flexibility to fit designs to smaller footprints, resulting in higher emplacement densities and hence higher thermal loadings. Such increased thermal loading could significantly increase both the maximum temperatures within the EBS and the duration of the thermal transient, which could have a large impact on kinetically-controlled chemical interactions.

Moving forward towards practical designs appropriate to Japanese repository conditions will inevitably require testing concepts underground at large (or full) scale. Modifications needed to ensure operational safety, practicality and quality assurance will have to be assessed in terms of their impact on long-term performance, probably via long-duration experiments (in conventional laboratories and underground, complemented by analogues if appropriate). Especially as there exists no obvious technology at present for non-invasive monitoring of the EBS, “post-mortem” analysis of large-scale, in-situ tests may provide a key component of the post-closure safety case.

In order to develop optimised designs for specific sites, it is important not only to have an integrated database of the required information from site characterisation and supporting R&D, but also a formal mechanism for supporting and documenting decisions. At the present, several implementing organisations (including NUMO) are investigating variants of “Requirements Management” for this purpose. Ideally, this tool can be integrated with the development of the information database (“Knowledge Management”) and assurance that required quality levels are maintained (“Quality Management”). 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 (e.g. JNC).

Safety Assessment

Although this is defined as part of NUMO’s repository concept, for the purposes of identifying R&D requirements it is worth considering SA as a separate topic, even though it clearly develops together with repository designs in an iterative manner. As noted above, a key development in this area from the basis provided by H12 is the need to include rigorous assessment of operational safety. As has clearly been seen by accidents in other countries (Gorleben, Germany: Bure, France), even during the first stages of site characterisation / repository construction, safety is a critical factor. Even the type of conventional (i.e. non-radiological) accidents common in the engineering and mining industries can cause major disruptions of repository programmes. Internationally, the safety of waste handling and emplacement has recently received increasing interest.

Because issues arise not only from risks during normal operations but also from disturbances from external perturbations, this is of particular relevance to Japan (e.g. consequences of earthquakes, recent great concern about risks from tsunamis). Extensive R&D will be needed to develop the tools and experience for the implementer to produce an operational Safety Case and for the regulator to adequately review it.

The post-closure SA in H12 was sufficient to demonstrate concept feasibility, but clearly limited in its ability to compare different design options or specific sites. In order to form the basis for evaluating different PIAs or DIAs and, later, supporting repository licensing, significant developments will be needed in basic safety assessment model chain (and supporting databases and "research models"), the development and analysis of scenarios and the management of uncertainties.

In terms of the main SA model chains, some areas where further R&D could be valuable include:

- EBS
    - Explicit representation of all engineered materials present (incl. liners, drains, plugs, seals, etc.)
    - Realistic representation of emplacement geometry (including consideration of interactions between individual waste packages)
    - Representation of variation in barrier properties with time (with explicit consideration of interfaces between different materials)
    - Inclusion of EDZ (with properties as function of time, if appropriate)
    - Robust representation of the RN release source-term
- Geosphere
    - Realistic representation of the near-field / geosphere interface
    - Consistent and reasonable representation of advective groundwater flow paths on all relevant spatial scales (macro – for assessing fluxes – to micro – for assign RN retardation)
    - Robust representation of RN retardation processes (sorption, matrix diffusion etc.)
    - Explicit consideration of the "usual problems" (colloids, organics, microbes)
- Biosphere
    - Site-specific representation of the geosphere / biosphere interface (as a function of time, if appropriate – e.g. in a coastal setting)
    - Development of Japanese-specific food-chain and dose conversion factor models (representing appropriate lifestyle conditions)

It should be borne in mind that the assumed geological barrier conditions in H12 tended to be rather favourable and volunteer sites may require a more realistic treatment (including mobilising "reserve FEPs") in order to support a robust safety case. The resulting model chain should be able to represent all important "groundwater" scenarios, considering gradual evolution of barrier properties. Further models will be needed to quantify perturbation or "what if?" scenarios.

A major part of post closure SA involves evaluation of the uncertainties; which are inevitable in the evaluation of behaviour over very long timescales. For such evaluation, deterministic calculations coupled to sensitivity analysis and probabilistic calculations may provide complementary information. In both cases, however, verification and validation of codes & associated databases is a continual challenge.

Finally, it should be emphasised that, as the programme advances, the level of the argumentation which the regulator is likely to require as support of the safety case is likely to increase (e.g. ITC, 2005). This will require much more subtle treatment of key processes. A good example here would be the very complex and strongly coupled geochemistry of the near field which is, at present, represented by simplistic material or element specific parameters (corrosion rates, solubilities, Kds, etc.) At present, resultant databases are neither complete, consistent nor validated (in all national programmes) but significant improvement would be possible if R&D resources could be focused on this problem (a possible future role for ENTRY / QUALITY).

Gaining acceptance of key stakeholders

The work outlined above is very much focused on meeting the requirement of ensuring development of a safe and well-structured repository programme. There are, however, further practical constraints on reaching key programme goals that are associated with gaining the acceptance of key groups, including:

- Local communities (municipality, prefecture)
- Local and national politicians
- Regulators
- National academic and professional expert groups
- International “radioactive waste community”

In order to gain such acceptance, it may be necessary to evaluate (or even implement) design variants that are not otherwise technically justified – e.g. extensive monitoring and institutional control, eased retrieval. Even though safety should not be compromised, there may be considerable benefit to be gained by working together with concerned groups to develop concepts that focus on the areas of most concern.

For the regulators and other expert groups, the technical arguments that support the formal SA to build the safety case may be of considerable importance (e.g. ITC, 2005). NUMO, together with key R&D groups, thus need to develop a “Safety Strategy” which establishes their national and international credibility and ensures that all required resources of infrastructure and trained manpower is available when required.

References

ITC (2005): Record of executive training course on the Safety Case, in preparation.

JNC (2000): “H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan”, JNC TN1410 2000-001 - 004.

NUMO (2004a): “Evaluating Site Suitability for a HLW repository“, NUMO-TR-04-04.

NUMO (2004b): “Development of Repository Concepts for Volunteer Siting Environment“, NUMO-TR-04-03.

NUMO & Posiva (2004): Proceedings of the bentonite-cement workshop, NUMO-TR-04-05.

PNC (1992): “Research and Development on Geological Disposal of High-level Radioactive Waste (H3)”, PNC TN1410 93-059.