Session I

GENERAL FRAMEWORK: CRYSTALLINE ROCKS AS HOST FORMATIONS

SAFETY FUNCTIONS OF CRYSTALLINE ROCK FORMATIONS IN DEEP GEOLOGICAL DISPOSAL AND THEIR HANDLING IN A SAFETY CASE – SKB'S SR-CAN EXAMPLE

A. Hedin[1], J. Andersson[2], R. Munier[1], J-O. Näslund[1], I. Puigdomenech[1], J-O. Selroos[1]
[1]Swedish Nuclear Fuel and Waste Management Co., [2]JA Steamflow AB, Sweden

Abstract

A number of detailed safety functions for a granitic host rock, subordinate to the main functions containment and retardation, are presented, based on SKB's safety assessment SR-Can for the KBS-3 concept. The host rock should provide a favourable environment for the repository from the point of view of chemical, hydraulic and radionuclide transport, mechanical and thermal properties, which are further specified as a number of subordinate safety functions. These are strongly linked to the functions and properties of the canister and the clay buffer in the KBS-3 concept. Issues related to geosphere stability during the one million year assessment period are discussed and primarily relate to perturbations caused by future colder and dryer climates yielding glacial and/or permafrost conditions and the impact these perturbations may have on the safety functions.

In the SR-Can assessment, it was concluded that the granitic host rocks at the analysed sites provide a sufficiently favourable and stable environment for the vast majority of the 6 000 analysed deposition holes. The residual radiological risks associated with the repository, as pessimistically calculated based on preliminary understanding of the two candidate sites, are, from the point of view of the host rock, sensitive to details in the repository layout. In particular, it is important to be able to avoid deposition holes intersected by large or highly transmissive and hydraulically connected fractures and thus to understand and being able to quantify the heterogeneous character of the fractured host rock, in particular at repository depth. A number of issues related to geosphere stability where improved knowledge could lead to more realistic assessments are also identified.

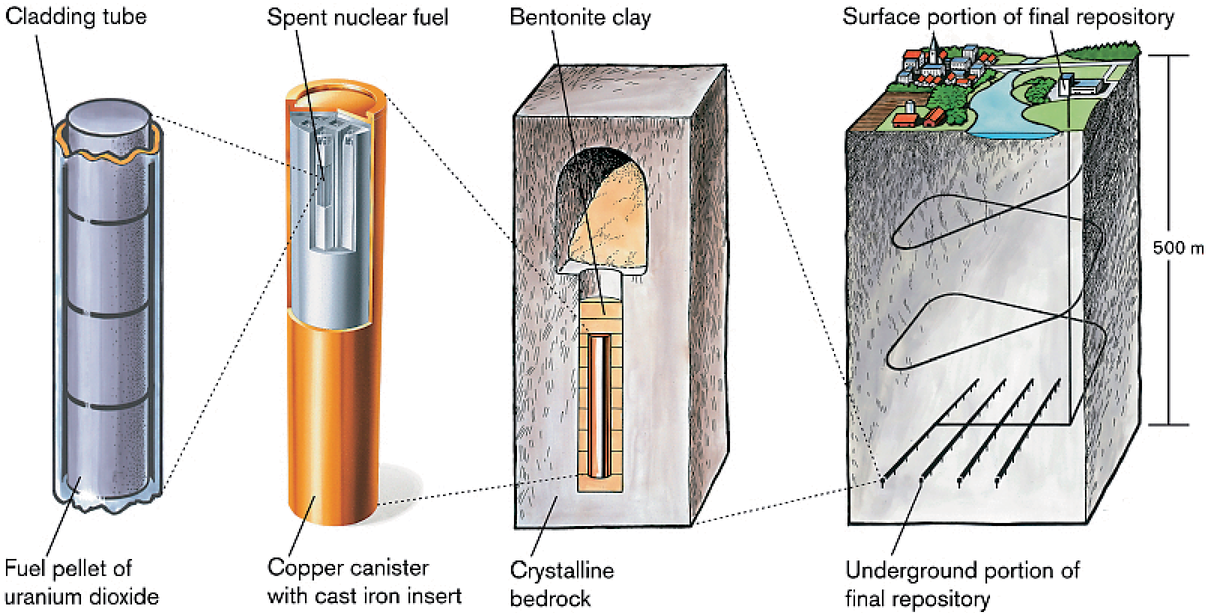
Introduction

Most of the material for this paper has been taken from SKB's safety report entitled "Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation; Main report of the SR-Can project." (SKB, 2006a). A main purpose of this so called SR-Can report was to establish a methodology for the coming SR-Site safety assessment in support of a licence application for a final repository in crystalline rock in Sweden.

The repository is of the KBS-3 type, where copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock, see Figure 1.

Site data for the SR-Can assessment were taken from an initial stage of SKB's ongoing investigations of candidate sites at Laxemar (municipality of Oskarshamn) and Forsmark (municipality of Östhammar). The sites were evaluated in comprehensive site modelling projects for Forsmark (SKB, 2005a) and Laxemar (SKB, 2006b).

Figure 1. **The KBS-3 concept for disposal of spent nuclear fuel**



The principal acceptance criterion according to Swedish legislation requires that "the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk". The time frame for the assessment is one million years after repository closure, in accordance with regulatory requirements.

Safety functions in the SR-Can assessment

The primary safety function of the KBS-3 concept is containment. Containment,[1] i.e. complete isolation of the spent nuclear fuel, is achieved by the canisters. The long-term properties of the surrounding buffer and crystalline host rock determine, together with the canister properties, how well this function is fulfilled, as will be further elaborated on in this paper.

The secondary safety function is retardation, i.e. the ability of the system to retard radionuclide transport from a potentially failed canister through the buffer and host rock to such an extent that release rates to the biosphere are low and that significant decay occurs prior to any releases to the biosphere. The buffer and the host rock and also a (partially) failed canister contribute to the retardation of the system.

The host rock should also isolate the repository from external phenomena and humans in the sense that it should provide a physical barrier between the waste and the surface environment in the vicinity of the repository.

---

[1] In the SR-Can report the term isolation rather than containment was used. The term containment is used here to better conform to internationally used terminology.

A detailed and quantitative understanding and evaluation of repository safety requires a more elaborate description of how the main safety functions of containment and retardation are maintained by the components of the repository. Based on the understanding of the properties of the components and the long-term evolution of the system, a number of subordinate safety functions to containment and retardation were identified in the safety assessment SR-Can (SKB, 2006a).

The following definitions are used in the SR-Can report:

- A safety function is a role through which a repository component contributes to safety.
- A safety function indicator is a measurable or calculable property of a repository component that indicates the extent to which a safety function is fulfilled.
- A safety function indicator criterion is a quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is maintained.

Safety functions are an aid in the evaluation of safety, but the fulfilment of all safety function indicator criteria is neither necessary nor sufficient to argue safety. Furthermore, safety functions are related to, but not the same as, design and siting criteria. Whereas the latter relate to the initial state of the repository, the former should be fulfilled throughout the assessment period.

Safety functions of the crystalline host rock in the SR-Can assessment

Subordinate safety functions to containment and retardation were defined for the canister, for the buffer, for the deposition tunnel backfill and for the gesophere, see Figure 2. The safety functions are interrelated as shown by the colour coding in the figure. The focus in this paper is on the geosphere, and it is obvious from figure 2 that the functions of the geosphere are strongly related to those of the other repository components. A general function of the host rock is to provide a favourable and stable environment for the repository. In more detail, the geosphere should:

- Provide chemically favourable conditions (function R1 in Figure 2).
- Provide favourable hydrologic and transport conditions (R2).
- Provide mechanically stable conditions (R3).
- Provide thermally favourable conditions (R4).

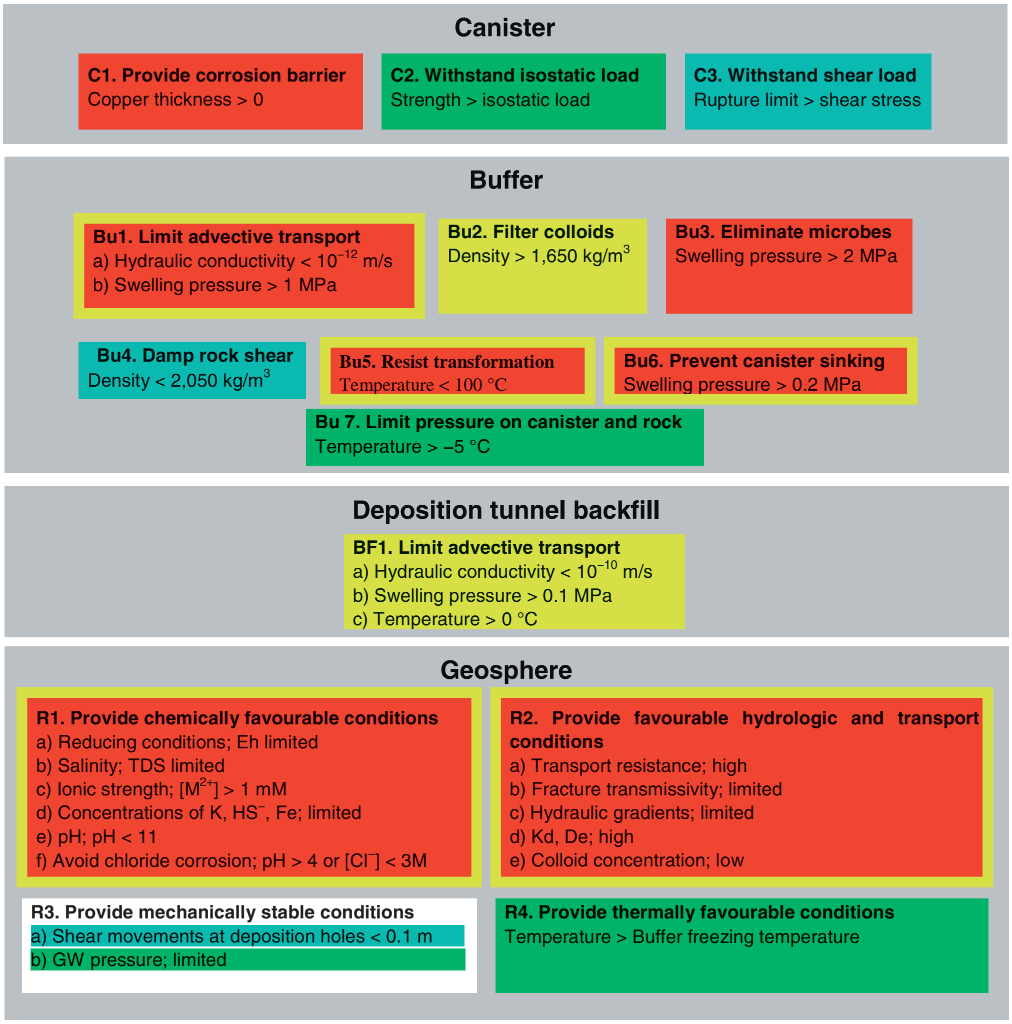
Each of these can be broken down into more detailed requirements on the long-term properties of the host rock.

The capability of the geosphere (the host rock) to provide a stable environment thus depends both on the long-term condition in the geosphere, but also on the requirements the repository concept puts on these conditions. The formulation of these requirements also depends on the status of understanding of the long-term processes that affect the long-term properties of the engineered parts of the repository.

Additional functions with respect to isolation can be formulated for the geosphere, but this was not done in the SR-Can assessment. In this context, indicators would relate to, for example, the absence of minerals in the bedrock and to repository depth.

In the following, a more detailed account of the safety functions relating to the geosphere is given.

Figure 2. **Safety functions (bold), safety function indicators and safety function indicator criteria. When quantitative criteria cannot be given, terms like "high", "low" and "limited" are used to indicate favourable values of the safety function indicators. The colour coding shows how the functions contribute to the canister safety functions C1 (red), C2 (green), C3 (blue) or to retardation (yellow). Many functions contribute to both C1 and retardation (red box with yellow board).**



Chemically favourable conditions

Reducing conditions

A fundamental requirement is that of reducing conditions. A necessary condition is the absence of dissolved oxygen, because any evidence of its presence would indicate oxidising conditions. The presence of reducing agents that react quickly with O_2, such as Fe(II) and sulfide is sufficient to indicate reducing conditions.

This requirement ensures that canister corrosion due to oxygen dissolved in the groundwater is avoided. Furthermore, should a canister be penetrated, reducing conditions are essential to ensure a low dissolution rate of the fuel matrix, to ensure favourable solubilities of several radioelements and, for some elements, also redox states favourable for sorption in the buffer, the backfill and the host rock.

Ionic strength, salinity

The salinity of the groundwater should neither be too high, nor too low. The total concentration of divalent cations should exceed 1 mM in order to avoid colloid release from buffer and backfill.

Groundwaters of high ionic strengths would have a negative impact on the buffer and backfill properties, in particular on the backfill swelling pressure and hydraulic conductivity. In general, ionic strengths corresponding to NaCl concentrations of approximately 35 g/l (0.6 M NaCl) are an upper limit for maintaining backfill properties whereas the corresponding limit for the buffer is around 100 g/l (1.7 M NaCl). The limit of tolerable ionic strength is however highly dependent on the material properties of these components.

Colloid concentrations

The concentration of natural colloids should be low to avoid transport of radionuclides mediated by colloids. The stability of colloids is much decreased if the concentration of divalent cations exceeds 1 mM, a condition that, as discussed above, is also required for the stability of the buffer and backfill.

Concentrations of detrimental agents

Regarding canister corrosion, there should be low groundwater concentrations of other canister-corroding agents, in particular sulphide, HS^-. For sulphide to pose a problem, earlier assessments demonstrated that considerably higher concentrations than have ever been observed in Swedish groundwaters would be required. The quantitative extent of such corrosion also depends on the groundwater flow around the deposition hole and on the transport properties of fractures intersecting the hole.

Furthermore, low groundwater concentrations of agents detrimental to long-term stability of the buffer and backfill, in particular potassium and iron, are desirable.

pH

Regarding groundwater pH, a criterion of $pH < 11$ can be formulated from the point of view of buffer and backfill stability. This is fulfilled for any natural groundwater in Sweden. However, construction and stray materials in the repository, in particular concrete, could contaminate the groundwater such that high pH values are reached.

Avoiding chloride corrosion

A further requirement is that the combination of low pH values ($pH<4$) and high chloride concentrations ($[Cl^-] > 3M$) should be avoided in order to exclude chloride corrosion of the canister.

Favourable hydrologic and transport conditions

The hydrologic and transport conditions in the geosphere are determined in a complex fashion by hydraulic gradients, fracture transmissivities and fracture hydraulic connections which result *i*) in differing flow conditions in the rock adjacent to different deposition holes and *ii*) in different transport resistances for the migration paths to and from the deposition holes. The retardation also depends on colloid concentrations and matrix properties. It is difficult to formulate more detailed criteria on these indicators than that they should have favourable values, as shown in Figure 2.

Mechanically stable conditions

The mechanical stability of the host rock cannot, in most respects, be simply evaluated. However, two main reasons for potential mechanical failure of the canisters can be identified. These are isostatic collapse and failure due to earthquakes causing secondary movements on fractures intersecting deposition holes. A strongly contributing factor to the former could be high groundwater pressures such as might occur during a glaciation. It is thus desirable that such pressures should be as low as possible.

Addressing the latter failure mode requires a complex evaluation of shear movements for a range of mechanical load situations. For assessing the consequences of such movements, a pessimistic limit on a maximally allowed shear displacement of a fracture intersecting a deposition hole can be formulated for canister integrity to be maintained. Based on results of modelling of the impact of rock shear movements on the buffer/canister system, a failure criterion of 10 cm for rock fracture shear movements across deposition holes was used in SR-Can. In view of current knowledge, this criterion is robust and possibly overly pessimistic.

In the shorter time frame it is also important to ensure that the mechanical loads generated from the heat of the spent fuel do not result in spalling. This impact can, however, both be predicted and at least partially mitigated by proper design.

Favourable thermal conditions

In quantitative terms, favourable thermal conditions imply that the host rock temperature at repository depth should exceed the buffer freezing temperature of −5°C. The main factors controlling this temperature are the host rock thermal conductivity and thermal capacity, repository depth and the temperature boundary conditions at the surface. Maximum repository temperatures are avoided by proper design. Here, the thermal conductivity is the key geosphere property.

Handling of rock safety functions in the SR-Can assessment

A general task in the evaluation of the host rock in a safety assessment amounts to determining the extent to which the geosphere safety functions are fulfilled throughout the assessment period. Note, however, that the fulfilment of the safety functions for the host rock alone is not sufficient for claiming safety and consequences need to be evaluated both in the case where the functions are upheld and where they are not.

For a properly selected site, it can be expected that the safety functions are upheld initially. This is indeed the case for the two sites analysed in SR-Can. Apart from being a conclusion in SR-Can, this was concluded in preliminary safety evaluations (SKB, 2005b and 2006c) where early results from the site investigations were evaluated against previously established criteria (Andersson *et al.,* 2000) for site suitability.

The main challenge for the assessment is thus to evaluate whether the functions are compromised over time. In particular, is the host rock resilient to the disturbances it will experience in the long term? Resilience will have to be evaluated in relation to the engineered structures for which the rock provides an environment.

From a safety assessment perspective short-term thermal, mechanical, hydraulic and chemical transients caused by the excavation and operation of the repository are expected on the time-scale of years to hundreds of years.

The main disturbances to the host rock conditions emanate from large-scale geological factors and impacts from the surface. Also future human actions may impact the safety functions of the gesophere.

Regarding large-scale geological alterations, the conclusion in the SR-Can assessment is that alterations of external conditions caused by processes such as tectonic movements, weathering and erosion are of minor importance for repository safety within the assessment period of one million years.

Surface changes are primarily related to changes in climate. In Sweden, extensive alterations to the present climate can be foreseen in the long term. Both a warmer climate and extended periods of permafrost and glacial conditions must be considered as likely during the one million year assessment period. Successive episodes of permafrost and glacial conditions are deemed to induce the largest alterations at repository depth.

Freezing of bedrock and groundwater, shore-level displacement and the presence of ice sheets will change permeability, water turnover, groundwater pressures, groundwater flow and composition. The ice load will alter rock stresses and during different phases of a glaciation the principal stresses will change in magnitude and in some cases also in direction. This will alter bedrock permeability and may also cause glacially induced faulting. In general, the integrated effects of continuous climatic evolution need to be considered, but there are also a number of more specific phenomena of importance for repository safety that require special attention. For the KBS-3 concept these include (SKB, 2006a):

- The maximum hydrostatic pressure and rock stress occurring at repository depth for glacial conditions (related to safety function R3b in Figure 2).
- The maximum permafrost depth throughout a glacial cycle (R4).
- The possible penetration of oxygen to deep groundwaters during glacial conditions (R1a).
- The possible occurrence of dilute groundwaters during glacial conditions potentially causing erosion of buffer and backfill (R1c).
- The groundwater salinity occurring at repository depth (R1c).
- Faulting (or more particularly movement on existing faults) associated with glaciations (R3a).
- Factors affecting retardation in the geosphere, like high groundwater fluxes and mechanical influences on permeability (R2).

Analyses in the SR-Can safety assessment

In the safety assessment SR-Can, a main scenario, where the external conditions were based on model reconstructions of the last glacial cycle, the Weichselian, was analysed as a starting point and all safety functions were evaluated for this scenario.

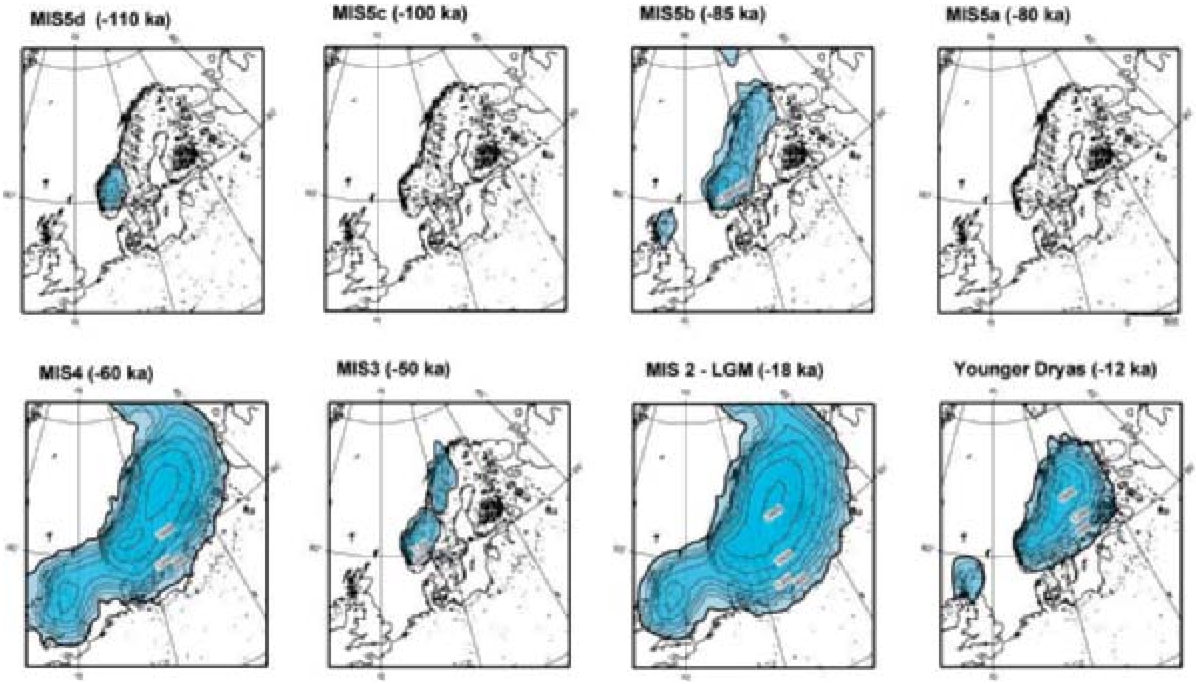
Additional scenarios were analysed to investigate whether any uncertainties not addressed in the main scenario could possibly jeopardise the repository safety functions further than was (possibly) the case in the main scenario. In these scenarios, more severe climate conditions than those in the reconstruction of the Weichselian, such as extreme permafrost depths and ice sheet thicknesses, were systematically evaluated. Radiological consequences for scenarios that could not be ruled out based on likelihood were calculated and included in a risk summation for the repository.

The following is a brief account of approaches used in the analysis of aspects of repository evolution related to the long-term properties of the host rock.

External conditions were analysed with a thermodynamic ice-sheet model and a model describing the global isostatic adjustment (GIA) to account for sea-level changes determined by the time-dependent ice sheet configuration in combination with the structure and properties of the solid Earth and its response to surface loading, see further (SKB, 2006a; Näslund, 2007). Figure 3 shows a model reconstruction of the ice-sheet for the Weichselian glacial cycle.

The thermal evolution in the bedrock was analysed with a permafrost model that obtains boundary conditions from the ice-sheet and GIA models (SKB, 2006a; Näslund, 2007).

Figure 3. **Modelled ice-sheets for the Weichselian reference evolution. Contour lines show ice-surface elevation with a 300 m contour interval. All maps show present day shore-line position.**



A number of mechanical aspects need to be considered, for example the possibility of large earthquakes occurring preferentially at the end of a glacial episode and the consequences this could have in terms of secondary movements in rock fractures (SKB, 2006a; Hökmark *et al.*, 2007) and, ultimately, on canister integrity. Other mechanical effects concern the general evolution of rock stresses during a glacial episode (SKB, 2006a) and possible consequences in terms of fracture movements, influence on hydrological properties etc. These latter issues were primarily addressed in SR-Can and will be further treated in the coming SR-Site assessment.

The hydrogeological evolution during a glacial episode was studied with a model simulation that obtained hydrological boundary conditions from the ice model. Both density-driven flow and rock matrix diffusion of salt were included in the modelling. The Darcy velocity, salt concentration in the flowing fractures, and salt concentration in the matrix at repository depth were obtained as a function of time. Also here, additional studies are foreseen in the SR-Site assessment.

In SR-Can the evaluation of the geochemical evolution is restricted to using separate specifications for the different climatic domains. Different groundwater compositions were assumed to prevail around the repository as a result of the different types of climate domains and their corresponding hydraulic conditions, whereas, in reality, the evolution between climate domains is expected to be gradual, without a clear boundary between them. For permafrost and glacial conditions, the following issues are treated, mostly by a combination of model studies and expert judgements:

- evolution of salinity;
- evolution of redox conditions;
- evolution of concentrations of other relevant natural groundwater components; and
- effects of grouting, shotcreting and concrete on pH.

Results from the SR-Can safety assessment

In summary, the following conclusions were reached when the selected scenarios were analysed. Most of these results relate to one or more of the geosphere safety function in Figure 2.

- Freezing of an intact buffer (relevant to geosphere safety function R4 in Figure 2) is assessed as ruled out for both the analysed sites, even for the most pessimistic and bounding climate conditions considered. For a water-filled cavity in an eroded buffer, freezing is not entirely ruled out for the most pessimistically chosen climate development at Forsmark, but calculations demonstrate that the mechanical pressure on the canister is acceptable in such cases.

- Canister failure due to isostatic load (R3b) is assessed as ruled out for both sites, also for the most severe and bounding future glacial conditions considered.

- Oxygen penetration to repository depth (R1a) for enhanced groundwater flows under an ice sheet, jeopardising the favourable reducing chemical conditions, is assessed as ruled out. This result is in agreement with conclusions from several earlier assessments. The modelling example in SR-Can is, however, stylised and simplified, meaning that additional analyses are warranted to increase confidence in the results. Such studies will be undertaken in SR-Site.

- Canister failures due to post-glacial earthquakes (R3a) cannot be completely ruled out. The risk contribution from this failure mode is, however, small. Probabilistic analyses in SR-Can imply that, on average, it would take considerably more than one million years for even one such canister failure to occur.

- Substantial loss of buffer through buffer erosion/colloid release may occur as a result of intrusion of low ionic strength glacial melt waters (R1c) in a 100 000 year perspective. The knowledge of the processes involved is uncertain and further research is being undertaken as a matter of priority.

- Loss of buffer mass, to the extent that advective conditions prevail in the buffer, which cannot be ruled out in a 100 000 year perspective, will lead to enhanced canister corrosion rates (R1d, R2). In a one million year perspective, this may lead to failures of some tens of canisters for the pessimistic hydraulic interpretation of the Forsmark site, with cautious assumptions regarding sulphide concentrations and cautious assumptions regarding deposition hole acceptance rules.

- A prolonged period of temperate climate is deemed as beneficial for safety, since the processes that are potentially the most detrimental to repository safety are related to glacial conditions. This concerns in particular the two main contributions to the calculated risk in SR-Can, namely i) potential buffer erosion with subsequent enhanced canister corrosion as a result of intrusion of glacial melt waters (R1c) and ii) the occurrence of large earthquakes during deglaciation (R3a). Further evaluations of the geochemical evolution for a prolonged warm period are required in order to better substantiate the conclusion that the geochemical conditions would remain beneficial.
- It is crucial to avoid deposition positions intersected by large or highly water conductive fractures (R2, R3a). The main risk contributors in the SR-Can assessment are related to the occurrence of large and/or highly transmissive fractures intersecting deposition holes. This applies to the buffer colloid release process and the impact of major earthquakes in the vicinity of the repository. The extent to which such positions can be identified and avoided is uncertain and there is a need for further studies.
- Radiological consequences were calculated for the two failure modes that could not be ruled out in a million year perspective, i.e. failures due to corrosion when the buffer is lost and failures due to fracture shear movements induced by large earthquakes in the vicinity of the repository. These show that potential releases from repositories at both Forsmark and Laxemar comply with the risk criterion issued by the Swedish Radiation Protection Authority.
- In an additional release calculation, a purely hypothetical case was studied where the canister and the buffer in all deposition holes were assumed to be lost, i.e. a hypothetical case with no containment and where the retardation is provided solely by the geosphere. In this case, calculated for the Forsmark site, the regulatory risk criterion is exceeded, but the geosphere retention (R2) alone is sufficient to limit the calculated doses to being comparable to the background radiation in Sweden.
- The importance of the excavation damaged zone (EDZ, R2) around deposition tunnels is limited in comparison to other transport routes for radionuclides, even for very pessimistic assumptions about the EDZ in relation to the reference excavation method.
- Thermally induced spalling around deposition holes may have a considerable impact on mass exchange between the flowing groundwater and the buffer (R2) as long as diffusion is the dominant transport mechanism in the buffer. There are uncertainties regarding the extent and the consequences of spalling and further studies are required.

Conclusions

The three main safety functions of the host rock are i) to provide a favourable environment for the containment of the spent fuel in canisters, ii) to provide retardation of radionuclides released from a potentially imperfect containment, and iii) to provide isolation of the waste from the surface environment.

In general, the potential of a granitic host rock to fulfil its safety functions related to the repository's capacity for containment are closely linked to the repository concept. For a KBS-3 repository in granitic rock, the requirements on the host rock are derived from the safety functions of the canister and the buffer. The long-term stability of the host rock must, therefore, be evaluated in the context of the requirements posed by the engineered barriers. This also means that an identified weakness in the capacity of the host rock can potentially be reduced or eliminated through engineering measures, through which the requirements on the host rock can be relaxed. For example, a stronger canister could be envisaged should the mechanical stability of the geosphere be deemed insufficient. The geosphere stability must also be seen in the light of the understanding of the long-term processes that could be detrimental to the engineered repository components. A thorough understanding of processes related to the long-term evolution of the EBS is necessary for the formulation of sound requirements on the host rock.

The retardation capacity of the host rock is more directly related to the rock properties, rather than being a result of the interplay between host rock and repository.

In the SR-Can assessment, it was concluded that the granitic host rocks at the analysed sites provide a sufficiently favourable and stable environment for the vast majority of the 6 000 analysed deposition holes. The residual radiological risks associated with the repository, as pessimistically calculated based on preliminary understanding of the two candidate sites, are, from the point of view of the host rock, sensitive to details in the repository layout. In particular, it is important to be able to avoid deposition holes intersected by large or highly transmissive and hydraulically connected fractures and thus to understand and being able to quantify the heterogeneous character of the fractured host rock, in particular at repository depth.

Surface erosion and weathering effects of the geosphere have a negligible impact in a million year perspective and the capability of the geosphere to fulfil its isolating function (to provide a physical barrier between the waste and the surface environment) is thus upheld.

Perturbations of the long-term stable conditions in the host rock, with potentially negative consequences for safety, mainly occur during permafrost and glacial conditions for a KBS-3 repository located in Swedish granitic rock. Regarding time-scales, this means that the main challenges to geosphere stability occurs on the scale of tens of thousands to hundreds of thousands of years. However, mechanical perturbations in the initial phases, e.g. thermally induced spalling resulting from the thermal load, need also be considered, in order to ensure that favourable rock properties in the vicinity of deposition holes remain also after disposal.

Related to the above, it is not possible to predict future climate. It is, however, as demonstrated in the SR-Can assessment, fully possible to put bounds on the key external factors like maximum glacier thickness, maximum permafrost depth, etc, and thereby bound the perturbations on geosphere conditions that must be taken into account in a safety assessment.

Evaluation of issues related to the long-term conditions in the bedrock, in particular those related to permafrost and glacial conditions, made up a considerable fraction of the analyses and efforts in general in the SR-Can assessment. In particular evaluations of the effects of various perturbations on the engineered barriers required large efforts.

Remaining main scientific and technical challenges related to the geosphere, where improved understanding could lead to more realistic assessments relate to:

- the extent and consequences of thermally induced spalling;
- permafrost and glacial hydrology;
- permafrost and glacial geochemistry (sulphate and sulphide concentrations, oxygenated and dilute waters);
- effects on the buffer of dilute groundwaters;
- effects on the host rock and the EBS of large earthquakes; and
- the possibility of identifying and avoiding large fractures intersecting deposition holes.

References

Andersson J., A. Ström, C. Svemar, K-E. Almén, L.O. Ericsson, (2000), *What requirements does the KBS-3 repository make on the host rock? Geoscientific suitability indicatiors and criteria for siting and site evaluation*. SKB TR-00-12, Svensk Kärnbränslehantering AB.

Hökmark, H., B. Fälth and R. Munier (2007), *Fracture Reactivation in Response to Seismic Events*. These proceedings.

Näslund J-O., (2007), *Climate change and its potential impact on mechanical, hydraulic and chemical conditions.* These proceedings.

SKB (2005a), *Preliminary site description. Forsmark area – version 1.2*. SKB R-05-18. Svensk Kärnbränslehantering AB, Stockholm.

SKB (2005b), *Preliminary safety evaluation for the Forsmark area. Based on data and site descriptions after the initial site investigation stage*. SKB TR-05-16, Svensk Kärnbränslehantering AB.

SKB (2006a), *Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. Main Report of the SR-Can project*. SKB TR-06-09, Svensk Kärnbränslehantering AB, Stockholm.

SKB (2006b), *Preliminary site description. Laxemar subarea – version 1.2.* SKB R-06-10. Svensk Kärnbränslehantering AB, Stockholm.

SKB (2006c). *Preliminary safety evaluation for the Laxemar subarea. Based on data and site descriptions after the initial site investigation stage*. SKB TR-06-06, Svensk Kärnbränslehantering AB.

REGULATORY EXPECTATIONS CONCERNING THE CONFIDENCE IN GEOSPHERE STABILITY AND ITS HANDLING IN AN ENVIRONMENTAL SAFETY CASE

S.L. Duerden
Environment Agency of England & Wales

Abstract

The Environment Agency's guidance provides a framework to enable a developer to build an environmental safety case[1] to meet the regulatory principles and requirements against which it will be judged. The developer will need to collect and assemble all the evidence in support of post-closure environmental safety of the disposal facility, including multiple and complementary lines of reasoning and quantitative assessments, to build a robust environmental safety case. Building confidence in the environmental safety of a disposal facility and establishing a sound basis for regulatory decision making will rely on managing and assimilating information related to the geosphere, collected over some tens of years. The environmental safety case needs to be periodically reviewed to ensure that the regulatory principles continue to be addressed, to ensure that advances in understanding and technology are considered and implemented, where feasible, and to resolve the scientific and technical issues that are important to the post-closure environmental safety case.

Introduction

In 2006 the UK Government announced that deep geological disposal, coupled with safe and secure interim storage, is the way forward for the long-term management of the UK's higher activity radioactive wastes.[2] In June 2007 the UK Government and the Welsh and Northern Irish devolved administrations published a framework for the long term management of higher activity radioactive waste [1]. The document includes proposals for the way in which a site will be chosen to dispose[3] of higher activity radioactive waste and it seeks views, through a formal consultation process:

- on the technical aspects of designing and delivering a disposal facility;
- on the process and criteria to be used to decide where the facility should be located;
- how to engage most effectively with communities that might volunteer to host the facility.

---

[1] The Environment Agency uses the term "environmental safety case" to distinguish it from the term "safety case", which in the UK has an established meaning in operational nuclear safety.

[2] Higher activity waste are defined as the more radioactive wastes (ILW and HLW), where ILW is waste exceeding the levels of 4 gigabecquerels per tonne (GBq/te) of alpha or 12 (GBq/te) of beta/gamma activity, and HLW is waste in which the temperature may rise significantly due to the radioactive content and needs to be taken into account in design of storage or disposal facilities.

[3] The definition of "disposal", in the case of solid radioactive wastes, means emplacement in a facility where the intent at the time of emplacement is to leave the wastes in the facility permanently (even though features might be provided to enable retrieval).

Environment Agency principles, requirements and general expectations

The Environment Agency's aim is to ensure that radioactive wastes are disposed of in the most appropriate manner in order to protect the public and the environment, and to contribute to the UK's aim of sustainable development. In particular, we are responsible for assessing any application for a licence to dispose of higher activity radioactive wastes to a deep geological repository in England or Wales. In determining whether to grant a licence we will consider an application on its own merits in accordance with the extant UK and relevant international regulations. Any licence we grant will be subject to periodic review and the facility will be subject to inspection and regulation, by the Environment Agency, until the facility is closed and until the end of any predetermined period of post-closure management control.

The Environment Agency does not prescribe in detail how the developer should design and develop a disposal facility, nor how the developer should build an environmental safety case to support an application for a licence to operate such a facility. The developer should establish an appropriate approach in the context of the extant regulatory Guidance on Requirements for Authorisation ("GRA") [2],[4] and demonstrate that the design chosen provides performance that complies with regulatory criteria and assures protection of people and the environment. We will apply the four general principles when considering an application for a licence to dispose of radioactive waste to a deep geological disposal facility.

GRA Principle No. 1 – Independence of safety from controls

Following the disposal of radioactive waste, the closure of the disposal facility and the withdrawal of controls, the continued isolation of the waste from the accessible environment shall not depend on actions by future generations to maintain the integrity of the disposal system.

GRA Principle No. 2 – Effects in the future

Radioactive wastes shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.

GRA Principle No. 3 – Optimisation (as low as reasonably achievable)

The radiological detriment to members of the public that may result from the disposal of radioactive waste shall be as low as reasonably achievable, economic and social factors being taken into account.

GRA Principle No. 4 – Radiological protection standards

The assessed radiological impact of the disposal facility before withdrawal of control over the facility shall be consistent with the source-related and site-related dose constraints and, after withdrawal of control, with the risk target.

The GRA describes a number of more specific requirements underpinning these Principles, and we will explore some of these further in the context of the confidence in geosphere stability and its handling in an environmental safety case for a deep geological facility.

---

[4] We use "GRA" as shorthand to Environment Agency *et al.* (1997). We are currently reviewing the extant GRA and we expect to make a revised version available for public consultation in 2008. However, we do not expect the overall intent of these principles to change but rather we will aim to improve the clarity.

GRA Requirement R3 – Use of best practicable means

"The best practicable means shall be employed to ensure that any radioactivity coming from a facility will be such that doses to members of the public and risks to future populations are as low as reasonably achievable (ALARA)"

The use of best practicable means will, for example, involve exploring alternative host rocks and, at a selected site or sites, design variants with respect to depth and other aspects of layout. It will also involve consideration of aspects of construction, materials used and waste emplacement. The developer should demonstrate that the design is optimised such that any additional measures which might reasonably be taken to enhance the performance of the chosen design would be disproportionate to the reduction in dose or risk (Principle 3).

GRA Requirement R5 – Multiple-factor safety case

"The overall safety case for a specialised land disposal facility shall not depend unduly on any single component of the case."

A key task for the post-closure environmental safety case is to convince the regulators and the public that any radioactivity coming from a disposal facility will be such that risks to people and the environment in the future are as low as reasonably achievable and that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today (Principles 2 & 3). The case should muster all the evidence in support of post-closure environmental safety of the disposal facility, including multiple and complementary lines of reasoning and quantitative assessments.

We will require the developer to demonstrate a good and thorough understanding of the various components of the system and how they may or may not affect environmental safety, and to demonstrate a thorough understanding of the processes and events that may affect the performance of the disposal facility over time. A deep geological disposal facility will be a complex system employing multiple barriers, some of which may have more than one environmental safety function. The performance of the disposal facility will depend on the combination of barriers and their environmental safety functions. We will require the developer to demonstrate a multiple factor safety approach such that the environmental safety case does not depend unduly on any single environmental safety function.

At the early stages of site selection the developer will need to determine the sort of environmental safety case that could ultimately be made at a potential site or sites, evaluate how robust it may be, and develop a qualitative view on the chances of the site or sites being acceptable. This will involve identifying the key technical challenges and demonstrating confidence that they can be addressed. During the design, development and operation of the disposal facility, the developer needs to resolve the scientific and technical issues that are important to the post-closure environmental safety case, ensuring that key assumptions are well supported.

The selection of an appropriate site is paramount in disposal concepts where site features (e.g. the geosphere barrier) are key in developing a robust safety case. Geosphere performance is effectively fixed once a repository location has been selected. In contrast, there may be scope for continuing to optimise the design of the engineered barrier system up until closure of the facility.

GRA Requirement R6 – Site investigations

"The developer shall carry out a programme of investigations to provide information necessary for the safety case and to demonstrate the suitability of the site."

The developer will have to demonstrate that the geosphere is adequately characterised, understood and capable of analysis necessary to support the environmental safety case and that the characteristics of the geosphere combined with the materials of construction of the facility are such as to limit the release of radionuclides. This will include consideration of the lithology, stratigraphy, geochemistry, local and regional hydrogeology and the resource potential of the area. The developer will also need to demonstrate an understanding of any potential local and regional scale dynamic processes such as seismicity, tectonics and climate change and their potential effects on performance of the disposal facility. Many of these issues feedback and involve developing a good understanding of the site and the environmental safety case (see Requirement 5).

Geosphere stability considerations

It is not our intent to specify a work programme to support any application to dispose of radioactive waste, since it is the responsibility of the developer to identify the key issues that need to be addressed in order to make and support a robust environmental safety case. We will consider the lines of reasoning, and evidence gathered, in order to judge whether the safety case is consistent with our principles and requirements. These judgements will feed into our regulatory decisions. However, in the context of geosphere stability and its handling in the environmental safety case we have identified below what we consider may be some of the key issues.

Disposal facility layout and mining

In the early stages of site selection, issues associated with disposal facility layout and mining will be key. The developer will need to demonstrate that the chosen design or designs can be excavated and operated effectively and in accordance with the requirements of the environmental and safety regulators, that the design is appropriate for the selected host geology or preferred geologies, and to assess its contribution to long-term performance.

The possible effects of mining excavations on the chemical and physical properties of the geosphere will need to be considered. The excavation damage zone (EDZ) will be a complex zone around the disposal facility with specific mechanical and chemical characteristics caused by excavation. The developer will need to understand and characterise the potential effects of excavating the facility, for example, the impacts of the EDZ on near-field hydrogeology. The chemical and physical characteristics of the geosphere will need to be monitored during excavation and through the operational phase of the disposal facility to confirm assumptions in the environmental safety case. The developer will need to demonstrate an approach to identify and implement corrective actions to deal with any foreseeable geological or geotechnical problems that might arise during construction or operation of the disposal facility, be alert to the possibility that assumptions in the environmental safety case might not be realised in practice, and be prepared to make changes if the need arises.

The developer will need to establish a view on the long-term stability of the underground openings and any engineering required to maintain that stability over different timescales. For example, if open crown space is part of the chosen design the developer will need to assess the potential effects on performance of the disposal facility including, for example, the integrity of, and changes in, the rock mass above the crown over time, and the potential for, and consequences of, accumulation of water and gas in the open crown space.

Site investigation

In the early stages of site selection the developer will have to demonstrate that the geosphere at the potential site or sites can be characterised without undue difficulty, this may be accompanied by a simple quantitative assessment of how good or bad the site may be. The developer will also need to demonstrate an understanding of the possible effects of intrusive site investigations on the physical and chemical characteristics of the geosphere and consequences on the performance of the disposal facility.

Before excavating it will be essential to establish the baseline physical and chemical characteristics of the host rocks. The developer will need to determine whether the properties of the host rocks are as expected and remain compatible with the design, and to adapt and improve the design taking into account new data collected from site investigation and characterisation. After the disposal facility is excavated the developer will need to carry out further site investigations to confirm that the characteristics conform to key design requirements of the environmental safety case. Indeed, the experience reported in various NEA *fora* is that the few programmes reaching or getting close to implementation have had to devote more effort than expected to reconciling the real system as designed and built by engineers (and also as it will be at the time of closure) with the assumptions made in the environmental safety case.

Information from site investigation and characterisation will be collected throughout the project and we will expect the developer to maintain a good understanding of state-of-the-art site investigation and measurement techniques, and demonstrate that new developments are considered and implemented where appropriate.

The developer will need to consider the potential for natural resources to be identified in the vicinity of the site in the future and the consequences on geosphere stability and long-term performance of the disposal facility if these are likely to be exploited at any time in the future.

The developer will need to establish an understanding of the occurrence, extent and consequence of dynamic processes such as tectonics, seismicity, or fluid flow events. In the United Kingdom disruption by seismic events is not likely to be a major issue, nevertheless the developer needs to demonstrate that the potential for the site to be disrupted by seismic events has been considered. In particular, the potential for geological events to affect groundwater pathways and the integrity of barriers (e.g. shearing through the engineered facility with consequential disruption of emplaced wastes) and their overall effects on the integrity and performance of the disposal facility, will need to be considered.

Performance and Monitoring

Throughout the project the developer will need to assess whether key characteristsics of the geosphere continue to lie within the design target, and whether assumptions in the environmental safety case are realised. In particular, the developer will need to assess the effects from excavation and the consequences if engineering degrades, determine how far any effects are likely to propagate through the geosphere over time, and to assess the effects on the performance of the disposal facility.

The developer will also need to demonstrate an understanding of the nature and impacts of natural processes such as climate change and glaciation, with respect to the longer term effects on hydrogeological properties of the geosphere.

Modelling studies

We will expect the developer to provide details, methodologies and results from mathematical modelling studies to demonstrate an understanding of the characteristics and behaviour of the disposal facility and its components. Modelling will also be used for sensitivity testing and optioneering. Where the environmental safety case is dependent on the modelling approach, emphasis needs to be placed on building confidence in the models. In some areas, e.g. seismic survey data, there may be alternative interpretations of the data and therefore no conceptual model of the system which can be regarded as uniquely valid. The developer will be expected to show that the environmental safety case is not unduly sensitive to such alternative interpretations.

Treatment of uncertainties

Uncertainties are unavoidable in an environmental safety case for a deep geological disposal facility. The treatment of uncertainties is key to establishing a robust case and building confidence in the environmental safety of the facility. The developer will need to demonstrate a systematic approach to identifying and managing sources of uncertainty. Where practicable, measures should be implemented to reduce overall uncertainties and, where it is meaningful to do so, significant uncertainties should be quantified into numerical assessments of probability and consequence.

Summary

It is the responsibility of the developer of a disposal facility to provide an environmental safety case in support of any application for a licence to operate a facility for the disposal of solid radioactive waste. The Environment Agency is not responsible for prescribing in detail how a facility should be designed or built, nor how to produce the environmental safety case. However, our guidance provides a framework to enable a developer to build a case to meet the regulatory principles and requirements against which it will be judged. The developer will need to collect and assemble multiple and complementary lines of reasoning and evidence to build a robust case.

Information related to the geosphere will be gathered at different levels of detail throughout the project from conceptual design, through site selection, characterisation, excavation, operation and after closure. Managing and assimilating this information over tens of years to produce and develop a robust environmental safety case will be crucial in building confidence in the short and long-term environmental safety of a facility and to establish a sound basis to enable us to grant a licence. Furthermore, since disposals will not be regarded as complete until all the requirements of the post-closure environmental safety case have been met (including sealing and closure), the developer will be expected to periodically review the case to ensure that the regulatory principles continue to be addressed, in particular to ensure that advances in understanding and/or technology are considered and implemented, where feasible, within the context of optimisation.

In the early stages of site selection, the developer will need to demonstrate an engineering design (or designs) appropriate for the potential host rock or rocks, that it can be excavated and operated effectively and in accordance with the requirements of the environmental and safety regulators, and that the design is appropriate for the selected host geology or preferred geologies. The developer will also have to demonstrate that the geosphere at the potential site or sites can be adequately characterised.

Prior to excavation it will be essential to establish the baseline characteristics of the geosphere, to determine whether the geosphere characteristics, together with other features and materials of construction, are such that a facility can be excavated, operated and closed in accordance with the requirements of environmental safety, to identify and assess the possible consequences of processes that might alter these conditions, and to identify the nature and consequences of remaining uncertainties.

During excavation and throughout the operational period it will be essential to revisit these characteristics to determine whether they conform to key design properties and assumptions made in the environmental safety case, to assess whether predictions from modelling studies are realised in practice, to assess whether the system is performing as expected, and to address key uncertainties and build confidence.

References

1. Managing Radioactive Waste Safely: A framework for implementing geological disposal. 25 June 2007. Department for Environment, Food and Rural Affairs. www.defra.gov.uk

2. Environment Agency, Scottish Environment Protection Agency, and Department of the Environment for Northern Ireland (1997) *Radioactive Substances Act 1993: Disposal Facilities on Land for Low and Intermediate Level Radioactive Wastes: Guidance on Requirements for Authorisation.* Bristol: Environment Agency.

TABLE OF CONTENTS

Executive Summary 3
Introduction 9
Scope and Objectives of the Workshop 13
Synthesis of the Workshop 15
Poster Session 31
Conclusions 33

Session I

General Framework: Crystalline Rocks as Host Formations

Safety Functions of Crystalline Rock Formations in Deep Geological Disposal and Their Handling in a Safety Case – SKB's SR-CAN Example 45

Regulatory Expectations Concerning the Confidence in Geosphere Stability and its Handling in an Environmental Safety Case 57

Session II

Examples of Key Processes Affecting the Geosphere for Crystalline Rock

Likelihood of Tectonic Activity Affecting the Geological Stability of a Repository in Japan: Development of NUMO's ITM Methodology 67

Climate Change and its Potential Impact on Mechanical, Hydraulic and Chemical Conditions 77

Uplift and Erosion: Potential Impact on the Geological Environment 91

Predictability of the Evolution of Hydrogeological and Hydrogeochemical Systems; Geological Disposal of Nuclear Waste in Crystalline Rocks........ 99

Geological and Rock Mechanics Aspects of the Long-term Evolution of a Crystalline Rock Site... 109

Session III

Arguments to Support Confidence in the Stability of Crystalline Rocks as Potential Host Formations

Lithological History and Ductile Deformation: The Lessons for Long-term Stability of Large-scales Structures in the Olkiluoto 123

Stability and Predictability in Younger Crystalline Rock System: Japanese Islands Case 133

Developing Confidence in Stability and Predictability of a Repository in Unsaturated Tuffs 147

Session IV

Response and Resilience of Crystalline Rock to Natural Perturbations and Geosphere Evolution (buffering)

Fracture Reactivation in Response to Seismic Events 157

Buffering against Intrusion of Groundwater of Undesirable Composition 173

Understanding shield Groundwater Flow Domain Evolution during the Quaternary Period to Build Confidence in Repository Long-term Safety 185

Hydraulic and Hydrochemical Response to Seismic Events 197

Poster Session

Discipline-integrated Modelling Approach for Describing the Olkiluoto Crystalline Site in Finland 207

Study on Characterisation of Quaternary Tectonic Movement by Uplift Estimation using Fluvial Terraces 217

Examination of Earthquake Ground Motion in the Deep Underground Environment of Japan........ 227

Frequency of Fault Occurrence at Shallow Depths during Plio-pleistocene and Estimation of the Incident of New Faults 235

The Role of the Geoshpere in Posiva’s Safety Case 241

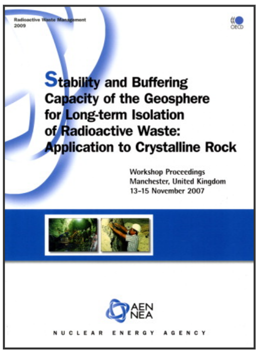
Understanding the Characteristics of Long-term Spatio-temporal Variation in Volcanism and the Continuity of the Related Phenomena for Estimating Regions of New Volcano Development . 247

Numerical Assessment of the Influence of Topographic and Climatic Perturbations on Groundwater Flow Conditions 257

Impacts of Natural Events and Processes on Groundwater Flow Conditions: A Case Study in the Horonobe Area, Hokkaido, Northern Japan 269

Groundwater Flow Prediction Method in Consideration of Long-term Topographic Changes of Uplift and Erosion 277

An Integrated Approach for Detecting Latent Magmatic Activity beneath Non-volcanic Regions: An Example form the Crystalline Iide Mountains, Northeast Japan 289



From:

Stability and Buffering Capacity of the Geosphere for Long-term Isolation of Radioactive Waste

Application to Crystalline Rock

Access the complete publication at:

https://doi.org/10.1787/9789264060579-en

Please cite this chapter as:

OECD/Nuclear Energy Agency (2009), “General Framework: Crystalline Rocks as Host Formations”, in *Stability and Buffering Capacity of the Geosphere for Long-term Isolation of Radioactive Waste: Application to Crystalline Rock*, OECD Publishing, Paris.

DOI: https://doi.org/10.1787/9789264060579-7-en