CONCLUSIONS

The workshop ended with an extensive period of discussion, followed by a presentation and discussion of the key concluding messages. The discussion period was initially divided into the subjects covered by the four sessions.

Session I

Many of the subjects that emerged during discussion of this session have already been reported under the description of the session itself. The two most significant points that were raised were:

- The fact that not all safety function criteria – or their equivalent in programmes outside Sweden – need to be fulfilled in order to ensure repository safety. The ultimate answer is given by integrated assessments, where the results are compared with dose/risk criteria. It is not always possible a priori to prioritise the ones considered to be the most important.
- There is no absolute measure of geosphere stability. Rather, stability must be judged in relation to the specific disposal concept or repository design being considered (and the site at which it is proposed to be located).

Session II

This session considered the key processes affecting the geosphere for crystalline rocks. A summary of the key processes raised during the presentations can be divided into two parts:

- The natural evolutionary processes that are considered relevant to geological disposal and
- The predictability of these processes over different times frames.

The natural evolutionary processes that are considered relevant to geological disposal

- During the early stage of site selection in Japan (i.e. selecting Preliminary Investigation Areas, PIAs) the main processes considered are volcanism and earthquakes or the occurrence of active faults. In later stages of the process, the occurrence of active faults is still relevant for the siting of the repository and its evolution over time.
- In northern Europe and Canada, the evolutionary processes triggered by climatic changes relevant to repository safety are: mechanical (e.g. changes in bedrock stresses), hydraulic (e.g. changes in groundwater flow) and chemical (e.g. changes in groundwater chemistry).
- Uplift and erosion can be linked to tectonic processes (plate tectonics and earthquakes) and/or climatic processes (e.g. isostatic rebound after melting of an ice sheet).
- Fracturing and faulting are correlated with any previous ductile deformation and past evolution of the stress field, with the implication that the fracture geometry is thus not fully stochastic. In rocks that are old, i.e. Precambrian, the majority of the fracturing took place in the long distant past.

The predictability of these processes over different time frames

The key message from the presentations is the importance of understanding past events, so that this information can be used to develop predictions of future conditions in a defensible manner:

- Climate changes in northern countries can be bounded sufficiently well up to at least 100 000 years into the future, based on the climatic records of the recent past (i.e. the most recent glacial cycle, the Weichselian), but detailed predictions are not possible. More recent climatic records can be used for predicting climatic changes for the next 10 000 years, e.g. in the situation of Yucca Mountain.
- Future changes in stresses that could modify groundwater flow paths are more difficult to predict, but the past geological evolution of the structures at a site can be used to place bounds on the changes that could occur in these stresses, triggered by processes such as the excavation of the repository, the thermal effects of the waste and the loading caused by future ice sheets.
- Changes in groundwater chemistry can be also bounded, by assessing site-specific hydrochemical and mineralogical observations that provide information on the past evolution of the site or of similar analogue sites (e.g. Yucca Mountain and Peña Blanca; other examples were presented in Session III).

The subsequent discussion raised the following points;

- The processes that are considered need to be associated with specific time frames, i.e. when they are significant for the safety of a repository. An example of this is spalling: it may be most prevalent during the thermal phase of the repository, and its most significant consequences may be during this phase; however, it may also have long-term consequences, if it results in the creation of faster transport pathways in the near-field.
- Where the exact consequences of a process are not well understood, e.g. the effect of glaciation in terms of the changes in stresses, there is often information that will allow us to place bounds on the impacts. In the case of glaciation, for example, the rock will have suffered from repeated glacial cycles and this provides evidence of the outer limits of potential impacts. In any case, the effects of such stress changes can be mitigated by using appropriate engineering (this subject is addressed in greater detail in the discussion of Session III).
- It is important to distinguish between processes that are significant and those that are perhaps interesting, but perhaps of limited impact. The Swedish regulators are, for example, interested in understanding whether there are what are termed “show stoppers”.

Session III

This session considered arguments to support confidence in the stability of crystalline rock as a potential host formation. A summary of the subjects raised during the presentations can be divided into three parts:

- Fracture regimes in stable geological environments, e.g. Scandinavia.
- Areas of active tectonics, e.g. Japan.
- The possibility of being able to bound adequately the likelihood and effects of perturbations.

Fracture regimes in stable geological environments,[13] *e.g. Scandinavia, Canadian Shield*

- Fracture patterns in Fennoscandia are generally very old, so, with the exception of shallow, post-glacial horizontal fractures formed due to stress relief, new fractures are not likely to be forming today or, except in exceptional circumstances (e.g. the Pärvie fault), to form in the future.
- Even stable tectonic environments can show deformation on brittle deformation zones – e.g. at Olkiluoto or end-glacial faults such as the Pärvie fault – but current deformation is not likely to have any significant impact on the intervening rock blocks.
- Although the fracture regime may be old and stable, its response to perturbations, e.g. changing stress patters and magnitudes, is spatially variable and time-dependent and relatively difficult to predict, but could be bounded (as demonstrated in SKB SR-Can).

Areas of active tectonics

- Even in areas of active tectonics, the overall patterns of the driving forces are generally constant, or change only slowly, over periods of 10^5 – 10^6 years. This provides a good framework for examining in more detail localised activity, e.g. local strain rates, magma intrusion, uplift etc.
- The difference in approach between the Swedish and Finnish and the Japanese evaluation of earthquakes and their effects can be summarised in the following manner:
  - In Japan it is possible to obtain detailed histories of fault activity by, for example, trenching. Large earthquakes are located on existing large active faults, and strain budget mapping (based on GPS strain, seismology and uplift/tilt data) can fill in the gaps in strain behaviour between these features. Current tectonic strains inland are predominantly taken up on upper crustal active faults, which can only extend relatively slowly, whilst new faults will nucleate and grow only slowly with time and therefore cannot host large earthquakes for a long time in the future. A key aspect of site selection is thus to identify and avoid active faults and their process zones.
  - Sweden and Finland have a single earthquake-generating mechanism for large events (i.e. due to glacial retreat) and faults do not have to have been demonstrably active to be susceptible to future activity (although similar length/magnitude ratios apply, i.e. it is not possible to have a large earthquake on a small fault). A conservative assumption thus needs to be used with regard to any future earthquake location. It is also generally not possible to obtain data on the past activity of specific faults.

The possibility of being able to bound adequately the likelihood and effects of perturbations

- How large can they be, what is their cause, how frequent are they and what are their characteristics?
  - Good confidence has been developed regarding predictions in this regard, at least related to tectonic activity. There are good modern geological analogues of tectonic and climatic events and processes.

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13. The term stable geological environment is being used here in the broadest sense to refer to the general geological stability of the rock mass. Its use does not preclude the necessity of investigating the geological stability of a particular potential disposal site, nor that the required level of geological stability for a particular site can only be found in certain parts of the world.

- Where and when will a perturbation occur?
  - This is more challenging to assess, but there are robust probabilistic techniques to examine this aspect. Where such probabilistic assessments are not deemed appropriate, deterministic analyses can be performed to assess the effects of potential perturbations and at least to bound (or even mitigate) the potential effects. It is also possible here to employ simple conservative assumptions, such as for example assuming that perturbations could occur on any deformation zone (e.g. SKB's approach in SR-Can).
- How much rock could be affected, either by rapid events or by slow perturbation processes?
  - To predict this aspect is also a challenge and predictions must be viewed cautiously. Nevertheless, there exist very good and increasingly sophisticated methods for examining this question, allowing modelling of what happens to groundwater and rocks that are distant from seismic events or volcanic sources, for example, or of how groundwater chemistry changes during a glacial cycle. Examples of and references to such work can be found, amongst many examples, in SR-97 (SKB, 2003 and in references therein), Miller and Marcos (2007) [for Olkiluoto], SKB (2007 and references therein), Bechtel SAIC (2004) [for Yucca Mountain].
- How much will the rock and the engineered barrier system (EBS) be affected?
  - In this area, better confidence can be achieved because there is good understanding of, for example, strain impacts on the EBS or the extent of oxygenated water under an ice sheet. In addition, there is the possibility of bounding the effects by making pessimistic assumptions.

There was some concern in the general discussion that the concept of stability tends to be used interchangeably with that of predictability. Most of the presentations discussed the exceptions from stability, though perhaps this was an example of demonstrating the rule by discussing the exceptions to it. In discussing the concept of stability with other (or broader) audiences, care should, therefore, be taken to ensure that its meaning is understood in the particular context of a disposal concept and/or of a specific site.

There was some surprise that analogues were not being used to a greater extent as, in geological terms, one million years is not such a long time, and analogues could be beneficial to help build understanding of the behaviour of specific aspects of a geological system. It was agreed that analogues did provide a good method of communicating ideas and concepts, but it was pointed out that, although in the past there have been some very good analogue programmes, it was perhaps less clear which questions they were being used to answer. That is, in using analogues it is important to be clear how they support a safety case. In this regard, it was emphasised that there is also a difference between examining the problem of radioactive waste disposal in general and in having a specific site for disposal; for a specific site, it is the features and processes at that site that are, obviously, of primary importance, and analogues are likely to have a secondary, supporting role.

Session IV

This session considered the response and resilience (i.e. buffering) of crystalline rock to natural perturbations and also geosphere evolution.

The main points raised during the presentations and the discussion were as follows:

- There is good and reliable evidence that the rapid changes evident at the surface are not transferred rapidly and with significant magnitudes to depth, though it is often more difficult to demonstrate this in crystalline rocks than is the case for argillaceous rocks. This is because argillaceous rocks are more likely to retain information on past hydrochemical and hydrogeological changes (see the NEA Workshop report on stability in argillaceous rocks).

- In a similar manner to Session III, the presentations tended to concentrate on the perturbations to these (inherently stable) geological systems, in order to demonstrate that they are well-buffered. It is important, however, not to overemphasise these instabilities, as this gives the impression that the geological systems are less stable than is actually the case. We must be scientifically precise and acknowledge uncertainties, but at the same time, in communicating our results and understanding, we need to convey our confidence in the stability of crystalline rock at depth.
- With this is mind, it is important to be internally consistent. There is always likely to be some evidence for instability, alongside evidence for stability, and this needs to be addressed and interpreted in terms of its implications for the overall performance of the repository system.
- It is possible to mitigate many, if not all, of the effects of external processes and events, e.g. earthquakes, by the optimal location and design of the repository.

A similar concern to that voiced in the general discussion of Session III was that we tend to use the concept of stability with that of predictability in an interchangeable manner.

Key concluding messages from the workshop

The key findings are presented under five headings:

1. The meaning of geosphere stability in the context of geological disposal.
2. The functions of the geosphere in geological disposal.
3. The geoscientific understanding of stability issues.
4. Geosphere stability in safety cases.
5. The effect of the assessment of geological stability on the location and layout of a repository.

1. The meaning of geosphere stability in the context of geological disposal

The stability of a crystalline rock is broadly defined as the presence of THMC conditions considered favourable for the safety of a radioactive waste repository, in line with the definition of the concept presented in the introduction. Stability, in this sense, does not imply that steady-state conditions exist; the geosphere is constantly evolving and such evolution is perfectly acceptable for safe geological disposal. What is important, however, is that we understand this evolution.

Conditions may well be favourable, despite the occurrence of THMC transients or alterations, caused by, for example, the construction of the repository, the effects of the waste or altered boundary conditions due to changing climate or tectonic activity.

It is important to understand that stability is not the same as predictability. Although it may be difficult to predict the extent and/or time of occurrence of a perturbation to the conditions in the host rock, it might well be possible to put bounds on its effects, such that it can be claimed that stability (in the above sense) is maintained. The concept of being able to place such bounds is an important element in investigating and analysing the effects of perturbations and is discussed below under Topics 3 and 4.

2. The functions of the geosphere in geological disposal

The main functions of a crystalline host rock for a radioactive waste repository are to contribute to containment of the radionuclides, mainly by providing a favourable environment for the repository, to contribute to retardation and to provide isolation.

As a repository programme and the accompanying process understanding advance and mature, it is possible to differentiate these functions into more detailed requirements or sub-functions. In general, all such sub-functions need not be fulfilled to ensure adequate safety – the ultimate answer is given by integrated assessments, where the results are compared with dose/risk criteria.

An important element in such a consideration is that the detailed requirements of the crystalline host rock are intimately linked to the repository concept being considered.

3. The geoscientific understanding of stability issues in crystalline rock

From a general viewpoint, crystalline rock formations are regarded as very stable and many (in Scandinavia and Canada in particular) have ages of the order of billions of years and with very limited surface erosion rates. This has been a prime reason in many countries for considering such formations for radioactive waste repositories. It needs to be emphasised, therefore, that many crystalline rocks provide intrinsically stable environments, particularly from a mechanical standpoint, and provide good buffering against external events and processes.

Considerably younger crystalline rocks have also been considered, e.g. in Japan, but their relative youth does not imply that they are, necessarily, any less stable, or less suitable for disposal purposes. There may, however, be intrinsic differences between such very old and relatively recent rocks, especially with regard to the types of deformation zones present and the variability of fracture orientations, which could have implications with regard to stability.

It is acknowledged that the properties and conditions of crystalline rocks evolve with time, but generally this evolution is limited and can be sufficiently well bounded. The use of proxy data, i.e. not data obtained from the site in question, is helpful in defining these bounds. There are constraints on the maximum and minimum values of many parameters which can be demonstrated using data from around the world; for example, the minimum separation distance from a seismically active fault that is necessary to limit the shear displacements on individual, suitably aligned fractures to less than a specified value, can be obtained by examining a suitable fault elsewhere in the world where such data have been obtained. The bounds thereby developed can be used as input to the bounding analyses referred to below under Topic 4.

The set of geosphere phenomena (processes and events) that could perturb the stability of a crystalline rock can be regarded as mature, as no fundamentally new phenomena have been identified in recent years. The phenomena include:

- Seismicity (e.g. with the reactivation of existing fractures, faults and deformation zones.)
- Volcanism.
- Uplift and erosion.
- Climate change (e.g. warmer and colder, including permafrost, ice sheets, sea level change.)
- Effects of excavation (e.g. spalling, EDZ.)

- Effects of waste emplacement (e.g. increased near-field temperatures, thermally-induced spalling.)
- Effects of microbial processes (although there were not treated in any detail at the workshop.)

The geoscientific understanding of these phenomena is advanced, and is, from a general viewpoint, still progressing in many areas. It is possible, therefore, to use such understanding to place defensible bounds on many of these effects and not simply to resort to taking a very conservative approach in safety assessments.

Regarding the understanding and handling of perturbations that affect the stability, the findings of the workshop can be broadly summarised as follows:

- There is, in general, good confidence in the understanding of the magnitude, cause, characteristics and frequency of perturbing phenomena.
- There is more limited confidence as to where and when a perturbation will occur.
- Confidence is also more limited regarding the volume of rock affected by a perturbation, but there are methods available to study such issues.
- The extent to which a repository is affected by a perturbation can often be conservatively addressed by using bounding and/or pessimistic approaches (see Topic 4).
- Conclusions regarding many of these phenomena are supported by the results of natural analogue studies.
- Such evidence is useful in supporting a safety case, but often relevant site-specific observations provide stronger evidence than those from a general natural analogue study.

4. Geosphere stability in safety cases in crystalline rocks

Any assessment of the long-term safety of a repository in crystalline rock will have to take into account uncertainties relating to geological stability. This is a natural part of the handling of uncertainties in a safety case and is also in agreement with requirements from regulators on the handling of uncertainties of relevance to safety.

There are assessment tools (deterministic, bounding and probabilistic) for addressing these uncertainties in a safety case and also a wealth of examples of how these tools have been applied to address the issues associated with geological stability in safety cases. Examples of the handling of issues include:

- Bounding estimates of maximum ice sheet thickness and bounding analyses of the consequences of these.
- Bounding estimates of maximum permafrost depth (or minimum repository temperatures) and bounding analyses of the consequences of these.
- Pessimistic assessments of the likelihood of earthquakes in the vicinity of a repository.
- Model studies resulting in bounding estimates of the consequences to the near-field of a repository of earthquake-induced secondary shear movements on fractures.
- Model studies resulting in bounding estimates of the consequences to the near-field of a repository of the effects of uplift and erosion.
- Pessimistic assessments of the likelihood and consequence of thermally-induced spalling.

- Bounding estimates of the impact on fracture transmissivity by future stress changes.
- Probabilistic assessments of future precipitation affecting groundwater flow and transport.
- The possibility of a warmer climate that would delay the onset of permafrost and glacial conditions and could thus be positive for safety cases where such issues are important, e.g. Scandinavia (although the effect may not necessarily be advantageous in countries where ice sheets and permafrost are not expected).

These bounding analyses carried out as part of a safety case are likely to provide pessimistic bounds, which are also likely to be broader than the bounds produced by the use of proxy data, as outlined under Topic 3 above.

The evolution of the geosphere and the associated stability issues must be evaluated in a repository and site-specific context. There are several examples of safety cases for a repository in crystalline rock where a comprehensive account of geosphere stability issues is given and where compliance with regulatory criteria is indicated. In these safety cases the geoscientific understanding of stability issues was found sufficient and not detrimental to safety:

- The handling of such issues often takes place by the application of bounding and/or pessimistic assumptions, as exemplified above.
- There is also room for more realistic treatments of many issues and this could lead to more realistic assessments of safety.

The handling of geosphere stability issues for extremely long time periods, typically beyond 10 000 or 100 000 years, depending on the case under consideration, remains a considerable undertaking in a safety case. The results of assessments of geosphere stability issues provide feedback to EBS design, to repository engineering and to some aspects of siting, with regard to the:

- Depth of the repository (e.g. providing transport paths with sufficient retardation, maintaining reducing conditions, avoiding permafrost, …) and to
- EBS design (canister thickness and strength to ensure resilience to mechanical loads …).

This feedback loop is an important mechanism for addressing geosphere stability issues in a waste management programme and applies equally to the issues discussed in Section 5 below.

Other aspects of repository siting are discussed below under Topic 5.

5. The effect of the assessment of geological stability on the location and layout of a repository

Analyses of the effects of perturbations, especially of a seismic nature, on the stability of the geosphere have shown that they have important implications for repository design and engineering, in particular related to the location of the repository in the rock mass and its detailed layout.

The potential impact of seismic events in controlling the location of the repository can be important on both the regional and local scales, with regard to providing a suitable separation of the repository from active or potentially active deformation zones or faults. At the repository scale, the effects of stress magnitude and stress orientation, combined with consideration of the potential reactivation of deformation zones and the larger fractures in future seismic events, provide important constraints on the location and orientation of disposal tunnels and on the positioning of waste canisters. In some geological environments (perhaps, for example, in Japan) the orientation of the maximum horizontal stress may be expected to remain approximately constant for a considerable time in the future, so that it is the effects of future seismicity that are of greatest interest. This appears also be the case in other countries, such as Sweden and Finland, where rotation of the stress tensor due to glacial advance may take place; here also, the greatest perturbation to the geological stability would be caused by a future seismic event during rapid glacial retreat.

It was agreed that the workshop had been a considerable success in helping to build confidence in the stability of crystalline rocks, which could provide hosts for a geological disposal facility for long-lived wastes.

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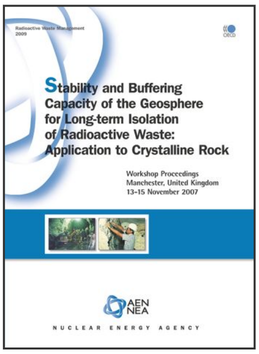
Response and Resilience of Crystalline Rock to Natural Perturbations and Geosphere Evolution (buffering)

Poster Session



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