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The Handling of Timescales in Assessing Post-closure Safety

Lessons Learnt from the April 2002 Workshop in Paris, France

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FOREWORD

The geological disposal of long-lived radioactive waste involves emplacement of the waste in a deep underground repository, sited and designed to ensure prolonged containment. The post-closure safety case for such a repository must consider times extending into the distant future, and phenomena and uncertainties that are characterised by widely differing timescales. The question of how to handle issues related to timescales in assessing post-closure safety is of concern to all national programmes.

The most appropriate ways of quantifying performance or safety may vary with time, as the repository and its environment evolve and different phenomena and uncertainties become relevant when evaluating its performance. The most common safety indicators are dose and risk, but, over certain time intervals, these may usefully be complemented by a number of other possible quantitative indicators and qualitative arguments for safety. Thus, it may be convenient to divide the post-closure period into a number of discrete "time frames", that are characterised by particular types of phenomena or uncertainties, and for which particular types of indicators or arguments are most suitable. This approach may also help in communicating and discussing the safety case with a wide range of audiences.

The issues described above provided the motivation for the NEA Integration Group for the Safety Case (IGSC) to support and organise a workshop entitled "The Handling of Timescales in Assessing Post-closure Safety". It was held in Paris on 16-18 April 2002 and hosted by the French Institute for Radiological Protection and Nuclear Safety (IRSN). The main objective of the workshop was to identify and discuss approaches related to and work done on timescales issues within national radioactive waste management programmes in the context of assessing post-closure safety of geological repositories.

This report presents the lessons learnt from this workshop and is intended to promote the better understanding of issues related to the handling of timescales in a safety case.

Acknowledgements

The report was prepared by Paul Smith, SAM Ltd., UK in collaboration with Peter De Preter (chairman of the workshop, ONDRAF/NIRAS, Belgium), Sylvie Voinis (NEA, France) and Trevor Sumerling (SAM Ltd., UK). It is largely based on ideas arising from the papers, oral presentations and discussions of the workshop on the "Handling of timescales in assessing post-closure safety" which took place in Paris on 16-18 April 2002 and was hosted by the IRSN (*Institut de Radioprotection et de Sûreté Nucléaire*, France). Not all points made in this summary document include a reference to the particular workshop paper, papers or presentations where they originated.

It was reviewed by Lucy Bailey (UK Nirex Ltd., UK), Lise Griffault (Andra, France), Alan Hooper (UK Nirex Ltd), Philippe Raimbault (DGSNR, France), Klaus-Jürgen Röhlig (GRS, Germany), David Sevougian (US-DOE YM, USA), Jürg Schneider (Nagra, Switzerland), Hiroyuki Umeki (NUMO, Japan), Abe van Luik (US-DOE-YM, USA), and Johannes Vigfusson (HSK, Switzerland)

The final report was agreed to by the Integration Group for the Safety Case (IGSC).

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1. INTRODUCTION

Geological repositories are sited, designed and operated to protect humans and the environment from the hazards associated with radioactive waste. Most challengingly, they are required to provide protection after their closure and over timescales that are considerably in excess of those commonly considered in most engineering projects. This requirement is laid down in international guidance and in many national regulations.

Protection is achieved by locating repositories deep underground, thus isolating the waste from the human environment. In addition, sites and designs are chosen that provide highly effective passive barriers to the release and migration of radioactive substances, the aim being to ensure that any releases of radioactivity to the human environment are very low.

The accepted approach for arriving at an adequate site and design is one of constrained optimisation [1]. In this approach, regulations set the process to achieve protection in terms of design optimisation and application of sound management and engineering practices, and maximum acceptable radiological consequences in terms of dose or risk criteria for hypothetical individuals living in the future. Siting, design and implementation proceed in a step-by-step process. At each step, a case for safety covering the period of repository construction and operation and also the period beyond the time of repository closure needs to be made. This must be adequate to support the decision at hand and to support any license application required. For post-closure safety, the safety case is defined as [2]:

> "… a collection of arguments … in support of the long-term safety of the repository".

The arguments are developed in a procedure termed safety assessment. Various processes and events could affect the evolution of a repository and its environment, and hence the containment and possible release of radioactive substances from the repository and their migration to the surface. These processes and events are characterised by timescales ranging from, say, a few tens or hundreds of years for transient processes associated with, for example, the resaturation of the repository and its immediate surroundings following closure, to perhaps millions of years for changes in the geological environment. Safety assessments must also consider whether any releases of radioactive substances lead to consequences greater than the targets set by regulation. In order to evaluate compliance with dose or risk criteria, assumptions must be made regarding the habits of potentially exposed groups (e.g. diet, lifestyle and land use), and these may change over timescales of just a few years.

The need to deal with such a wide range of timescales gives rise to a range of issues related to the methods and presentation of safety assessments. These issues are addressed in the present document. In particular:

- Is it really necessary to argue a case for safety over timescales of a million years or more and, if so?
- How predictable is the evolution of the repository and its environment over these timescales?
- What types of arguments are available that take account of the inevitable changes that occur over long timescales, as well as the uncertainties associated with these changes?
- How can public concerns affect the emphasis given to different types of argument at different times?

These issues are of concern to all national programmes and provided the motivation for the IGSC to support and organise a workshop entitled “The Handling of Timescales in Assessing Post-closure Safety”. The workshop was held in Paris on 16-18 April 2002 and was hosted by the French Institute for Radiological Protection and Nuclear Safety (IRSN) [3]. The findings of the workshop, referred to hereafter as the *timescales workshop*, provide the material on which the present document is based.

2. OVER WHAT TIMESCALE DOES A SAFETY CASE NEED TO BE MADE?

It is an ethical principle that the level of protection for humans and the environment that is applicable today should also be afforded to humans and the environment in the future. This is reflected in the IAEA Safety Fundamentals document [4], which states that "Radioactive waste 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". The principle implies that the safety implications of a repository need to be assessed for as long as the waste presents a hazard, and there is no ethical reason to restrict considerations of the safety implications to a more limited period, in spite of the technical difficulties that this can present to those conducting safety assessments.

There is inevitable uncertainty in predicting the real level of protection that will result for people that may live at the site of a repository at some time in the distant future. What can be aimed at, however, is to leave future generations an environment that is protected to a degree acceptable to our own generation. It is also relevant to observe that this level of protection will ensure that any radiological impacts due to disposal will not raise levels of radiation above the range that typically occurs naturally.

Ethical considerations regarding protection of humans and the environment apply not only to geological repositories for radioactive waste, but also to facilities for other types of waste. In practice, environmental assessments for these facilities typically address much shorter timescales – generally periods of tens or occasionally hundreds of years – even though the disposed substances may, in some cases, remain toxic indefinitely. It is, paradoxically, the finite, though sometimes long, half-lives of some of the isotopes in radioactive waste that seem to have set the timescales for many repository safety assessments. Another factor is the high degree of effectiveness with which deep geological disposal facilities are expected to contain radioactivity. Even for a well-sited and well-designed facility, releases of radioactive substances are inevitable, but will occur only very far in the future when much of the radioactivity will have decayed. Safety studies for deep geological repositories have tended to focus on the distant times when releases do eventually arise. This can be the result of regulatory requirements. In several countries, regulations require calculations of dose or risk to be carried out at least until the time that these safety indictors attain their maximum values, regardless of when this occurs. Regulations in Switzerland [5], for example, state that doses and risks "shall at no time" exceed specified values.

There is an increasing consensus among both implementers and regulators that, in carrying out safety assessments, calculations of dose or risk should not be extended to times beyond those for which the assumptions underlying the models and data used can be justified. At the least, the limits of applicability of the models and data should be acknowledged when a safety case is presented. In view of the way in which uncertainties generally increase with time, or simply for practical reasons, some cut-off time will inevitably be applied to calculations of dose and risk. This may be dictated by regulations, or it may be the result of a decision of the implementer or discussions between regulators and implementers. In the United Kingdom [6];

> "The timescales over which assessment results should be presented is a matter for the developer to consider and justify as adequate for the wastes and disposal facility concerned".

In the United States, a panel of the National Academy of Sciences suggested in 1995 that there was no reason to curtail the calculational time frame for a Yucca Mountain repository [7] until "approximately one million years" into the future, "after the geologic environment has changed, eroding the scientific basis" for the safety calculations and not allowing "useful information" to be developed by continuing such calculations. The United States Environmental Protection Agency (US EPA) considered this recommendation and decided to implement it in two parts. First, a rigorous evaluation of performance is required for 10 000 years that has to meet a prescribed limit. Beyond that time it is required to evaluate safety to the time of peak dose within the period of geologic stability (considered to a be a million years at Yucca Mountain), but the results of this longer term evaluation do not have to comply with the 10 000-year requirement. The US EPA explained concerning these latter calculations that [8]:

> "We have concerns regarding the uncertainties associated with such projections, and whether very long-term projections can be considered meaningful; however, existing performance assessment results indicate that the peak dose may occur beyond 10 000 years ... Such results may, therefore, give a more complete description of repository behaviour".

The US EPA requirements were incorporated into the US Nuclear Regulatory Commission regulations governing a Yucca Mountain repository [9]. This judgement regarding the meaningfulness of longer-term calculations is not universally shared, but a basic principle of agreement is that the rigour of estimates made to illustrate safety for any future time is dependent on the extent of the scientific basis supporting that evaluation.

This illustrates that, even where regulations prescribe a cut-off time for calculations of dose or risk, or the period where the results of such calculations must be compared to some limit or guideline (e.g. [8-10]), there is generally no cut-off time, or a very distant cut-off time, for the period to be addressed in some possibly less rigorous way in safety assessment, which is seen as a wider activity involving the development of a range of arguments for safety, such as those discussed in later sections of this document.

3. WHAT ARE THE LIMITS TO THE PREDICTABILITY OF THE REPOSITORY AND ITS ENVIRONMENT?

Repositories are typically sited in stable geological environments in which key characteristics that provide safety, such as mechanical stability, low groundwater flow and favourable geochemical conditions, are unlikely to change significantly in the course of time. Environments are generally chosen that are,

- unlikely to be affected by major tectonic movements, volcanic events or other geological phenomena that could give rise to rapid or sudden changes in geological or geochemical conditions,
- largely decoupled from events and processes occurring near the surface, including climate change, and
- lacking in natural resources that might attract exploratory drilling, thus minimising the possibility of inadvertent human intrusion in the future, when the location of the repository may no longer be known.

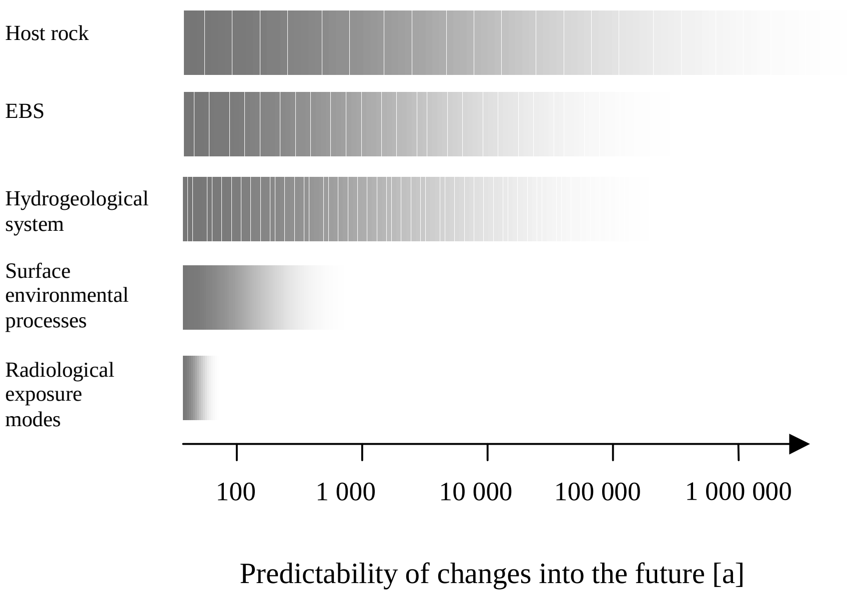
Repositories employ engineered materials that are, in general, well understood, and selected to be resistant to physical and chemical degradation under the conditions that are expected to prevail in the geological environment. In addition, they should not interact with each other or with the geological environment in a complex or poorly understood manner that could give rise to safety concerns. Complex interactions can sometimes occur, but the implications for safety are often mitigated by the characteristics of the repository and its environment, as discussed in Section 4.1.

Over long enough timescales, however, even the most stable engineered materials and geological environments are subject to perturbing events and changes. For example, the possibility of new features and deformation in the repository host rock must be considered over timescales in the order of, say, 10^5 or 10^6 years, no matter how carefully a site is chosen for its stability. These events and changes are subject to uncertainties, which generally increase with time and must be taken into account in safety assessments. Eventually, but at very different times for different parts of the system, uncertainties are so large that predictions regarding the evolution of the repository and its environment cannot meaningfully be made (see Box 1).

As discussed in the next section, arguments for safety can still be made that are likely to be adequate for repository licensing provided a repository is well designed and a suitable, geologically stable site is selected. Well-supported statements regarding the radiological consequences of such a repository can be made for the prolonged period over which the stability of the geological environment can be assured, whereas a less rigorous assessment of radiological consequences is likely to be adequate at later times, on account of radioactive decay and the resulting decreased radiological toxicity of the waste. Nevertheless, an acknowledgement of the limits of predictability of the system in both regulations and in safety cases is important for credibility in the eyes of the public and of other stakeholders.[1]

1. Here, a stakeholder is any institution, group or individual with a role to play in the process (see proceedings of the Forum of Stakeholders Committee (FSC) workshop, Paris, 2000).

Box 1. **The limits of predictability of various aspects of a geological disposal system (from Figure 1, p. 15 of [3])**



The figure gives a schematic illustration of the limits of predictability of various aspects of a geological disposal system (note that actual timescales are site- and design-specific). It illustrates that, at least for a well-chosen site, the evolution of the broad characteristics of the engineered barrier systems (EBS) and the host rock are reasonably predictable over a prolonged period (10^5 or 10^6 years, say, in the case of the host rock). There are uncertainties affecting the engineered barrier systems and the host rock over shorter timescales, but these can, in general, at least be bounded with some confidence. The patterns of groundwater flow (the hydrogeological system), in particular near the surface, can be affected by climate change and are thus somewhat less predictable. Surface environmental processes and radiological exposure modes are not generally considered to be parts of a deep geological repository system, but are relevant for evaluating dose and risk. These are less predictable still, being affected by ecological change, human activities and individual habits, which are highly uncertain, even on a timescale of a few years.

4. WHAT TYPES OF ARGUMENTS ARE AVAILABLE THAT TAKE ACCOUNT OF THE CHANGES AND UNCERTAINTIES ASSOCIATED WITH LONG TIMESCALES?

4.1 General considerations

This section discusses the various types of argument that can be made in order to build a convincing safety case. Safety assessments are increasingly taking into account a fuller range of arguments, including arguments based on safety and performance indicators that can be used in addition to dose and risk, and regulations are increasingly providing guidance regarding their use [11].

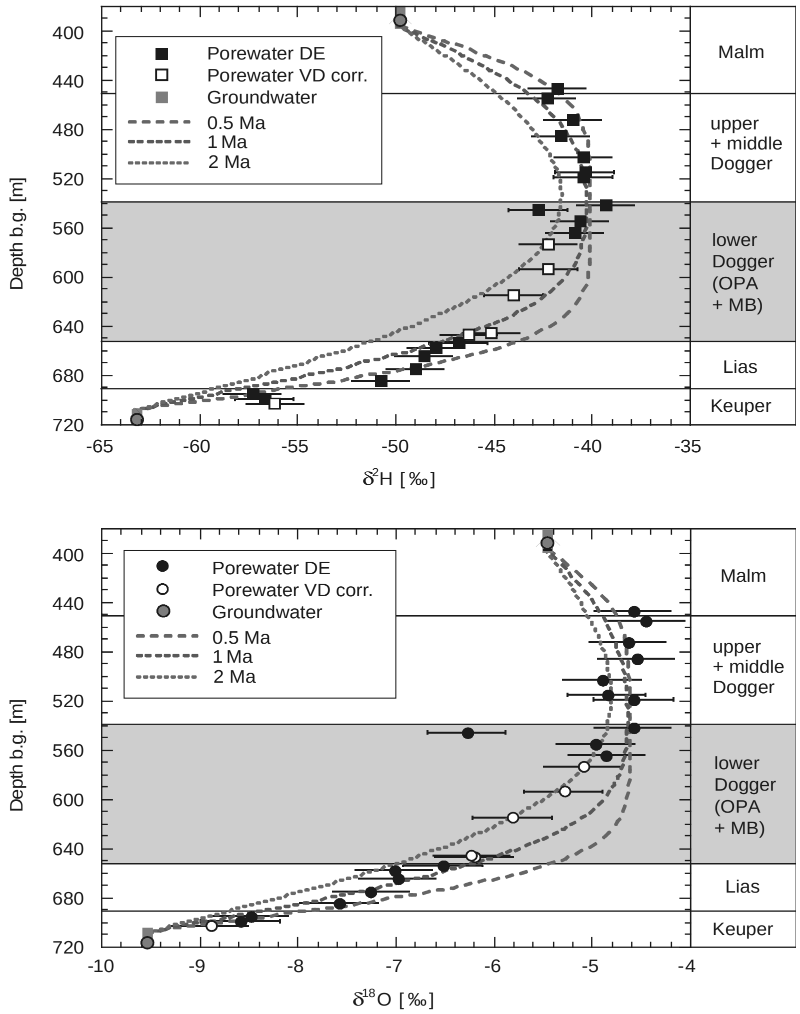
An important line of argument relates to the intrinsic quality of the site and design. The safety of any repository depends primarily on the favourable characteristics of the engineered materials and the geological environment, including their predictability over prolonged periods, and these characteristics need to be stressed in safety cases. In the case of the geological environment, evidence for stability and other favourable characteristics often comes from *in situ* observations and measurements, including measurements that relate to groundwater age and movement (e.g. natural isotope profiles in some argillaceous rocks, see Box 2), as well as palaeohydrogeological information in general. Such information is used to develop an understanding of the history of the geological environment, which can be used as a basis to predict its likely future evolution. Other types of arguments are based, for example, on thermodynamic, kinetic, and mass balance considerations. Arguments for the feasibility, in principle, of safe geological disposal, can also be made based on the existence of natural analogues and, in particular, natural uranium deposits (see Table 1).

Another aspect of the intrinsic quality of the site and design for most repositories is the fact that multiple barriers or processes contribute to safety. This is termed the "multi-barrier" or "multi-function" concept. As illustrated in Box 3, as conditions in the repository and its environment evolve over the course of time, some components can cease to perform certain functions and new functions come into operation. For example, canisters containing the waste may eventually become breached, following which the safety of the repository depends on, for example, geochemical immobilisation and retardation processes and the slow rate of groundwater movement within and around the repository. Complete containment in canisters, geochemical immobilisation, and the slow rate of groundwater movement are examples of "safety functions". The key point about the multi-barrier or multi-function concept is that if one component or process is less effective than expected, or becomes ineffective earlier than expected, then other barriers or processes, will to some extent take their place. This means that many uncertainties in the evolution of the repository and its environment have only limited implications for the overall safety of the system.

Table. 1. **Examples of the types of arguments that can be used to support the stability and other favourable characteristics of the repository and its environment**

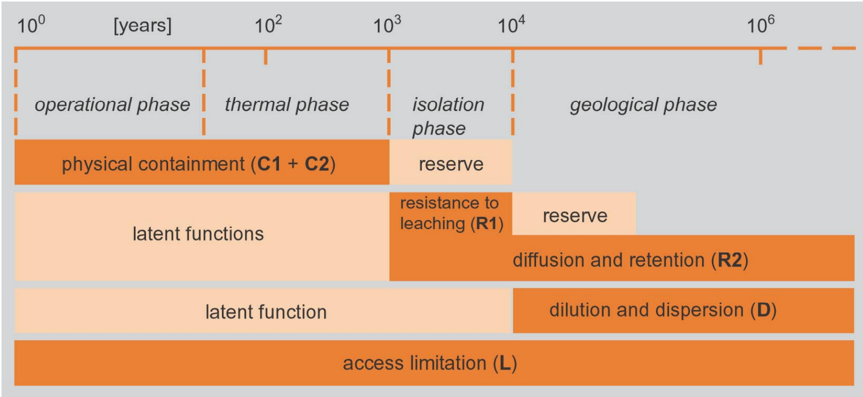
Types of argument	Examples of application
The existence of natural uranium deposits, and other natural analogues of a repository system or one or more of its components	Feasibility, in principle, of geological disposal; long-term stability of the host formation and of bentonite, which is used as a buffer material in many repository designs
Thermodynamic arguments	Stability of copper, which is used as a canister material in some designs, in deep groundwaters (e.g. [12])
Kinetic arguments	Corrosion rate of iron, which is also canister material in some designs;
Mass-balance arguments	Limited chemical alteration (illitisation) of bentonite; the slow rate of copper corrosion
Natural isotope profiles in some argillaceous rocks, groundwater ages and palaeohydrogeological information in general	Slow groundwater movement [13] and long-term stability of the geosphere (e.g. [14])
Laboratory experiments	Laboratory studies of, for example, glass dissolution.
Detailed modelling studies	Slow groundwater flow and radionuclide transport; low likelihood and consequences of earthquakes.

Box 2. **Isotope concentration profiles across the Opalinus Clay (OPA) and adjacent rock strata, comparing measured data obtained under various conditions (data points) and preliminary modelling results assuming diffusion only [14]**



The comparison provides evidence for the dominant role of diffusion in controlling porewater composition in the Opalinus Clay and, by analogy, in controlling the movement of any radionuclides released into those porewaters from a repository.

Box 3. **The four phases of the normal evolution of the proposed ONDRAF disposal system for high-level waste and the corresponding long-term safety functions [15]**



The long-term safety functions of the disposal system are "physical containment" (C1 – "water tightness" and C2 – "limitation of water infiltration"), "delaying and spreading of the release" (R1 – "resistance to leaching" and R2 – "diffusion and retention") and "limitation of access" (L); the long-term safety function of the environment of the disposal system is "dispersion and dilution" (D). A function is "latent" if it will operate partially or totally only if some other functions fails to perform as expected. Reserve functions are those that may operate partially or totally, but cannot currently be relied upon with confidence.

The use of long-lived canisters, as envisaged for most high-level waste repositories, is another more specific example of repository design mitigating the implications of uncertainties for safety. The performance of these canisters mitigates the effects of uncertainties associated with the complex and coupled thermal, hydraulic, mechanical and chemical processes that could occur during the transient phase following repository closure. If the canisters remain intact throughout the duration of the transient phase, then, provided the characteristics of the system after this phase can be well predicted, these uncertainties are of little relevance to safety.

Evidence for the intrinsic quality of the site and design alone is, however, insufficient to make a safety case that is adequate for repository licensing. All current national regulations also require arguments for safety to be made based on the evaluation of indicators such as dose and risk which can be compared to regulatory safety criteria. In order to test compliance with such criteria, scenarios for the evolution of the repository and its environment are derived and their radiological consequences evaluated using quantitative models. Evidence supporting the choice of scenarios, models and data can come from a wide range of sources, including field, laboratory and theoretical studies, and multiple lines of argument can often be made to support the choice of particular scenarios, model assumptions and parameter values.

Uncertainties nevertheless remain that affect the evaluation of consequences, and approaches to deal with these are discussed in the following sections. An overview of the approaches that are available is given in Section 4.2, followed by more detailed discussion of the use of so-called "stylised approaches" in Section 4.3 and the formulation and evaluation of scenarios for geological evolution in Section 4.4. Uncertainties can also, to some extent, be avoided by the use of safety and performance indicators that are complementary to dose and risk, as discussed in Section 4.5.

Finally, the emphasis placed on different lines of argument or different safety and performance indicators can also vary with time. As the repository and its environment evolve, uncertainties and their impact on safety change and the hazard presented by the waste decreases. This change in safety assessment approach with time is discussed in Section 4.6.

4.2 Approaches to deal with uncertainties

Many uncertainties can be quantified, or at least bounded, and methods exist to take these uncertainties into account in evaluating compliance with dose or risk criteria. These include:

- the use of pessimistically selected parameter values and conservative assumptions that ensure that models used to assess the radiological consequences err on the side of pessimism;[2] and
- the use of probabilistic techniques, or a set of individually performed deterministic calculations, in order to explore the range of possibilities for system evolution.

2. This may be acceptable, desirable or even required when demonstrating compliance with regulatory criteria, whereas a more realistic treatment is required for optimisation purposes and for the testing of models and databases.

Some uncertainties that can have a significant effect on evaluated levels of safety are, however, difficult to quantify or bound, and are less amenable to the methods mentioned above, particularly in cases where the range of possibilities is very wide or unpredictable. The evolution of the surface environment and the nature and timing of future human actions, for example, become highly speculative even over relatively short timescales, although bounds may be set, to some extent at least, based on human resource and dietary needs. Over much longer timescales, the formulation of scenarios for the evolution of the geological environment, the stability of which is a key element of the safety case for all deep geological repositories, becomes increasingly a matter of speculation. This presents particular difficulties because of the fundamental role of the geological environment in the multi-barrier or multi-function concept. This point is further dealt with in Section 4.4.

As discussed in later sections, stylised approaches can be used to address uncertainties in the evolution of the surface environment and the nature and timing of future human actions that are difficult to quantify or bound. It has also been suggested (at the timescales workshop) that such approaches could also be considered for the long-term evolution of the geological environment. Additional arguments for safety that do not require an explicit assessment of some uncertainties can also be constructed using safety and performance indicators complementary to dose and risk.

4.3 Stylised approaches

There are many largely unpredictable changes that could occur in the characteristics of society, human habits, technology and the surface environment over timescales of hundreds of years or less, with the likelihood of significant change increasing as longer times are considered. This is the reason why reliance on institutional control is generally limited to a few hundred years at the most. The greater stability of the geological environment compared to the surface environment is a key argument in favour of geological disposal as a management option for long-lived and highly radioactive waste.

Assumptions regarding the characteristics of the surface environment and the nature of future human society and actions must nevertheless be made if dose and risk are to be evaluated and tested against regulatory and design targets. There is international consensus that a “stylised approach” is an appropriate means to define these assumptions. This approach has been discussed extensively in international fora, e.g. within an NEA *ad hoc* group

[16] and within the IAEA BIOMASS[3] project [17-21]. The approach involves defining a range of alternative “credible illustrations” or “stylised situations”, including, for example, different possible future climate states, agricultural practices and exposure pathways, and analysing the resultant dose or risk for hypothetical critical groups. This avoids open-ended speculation on issues such as future human habits for which uncertainties are large and irreducible.

In Finland and in the United States, it is the regulator that defines the exposure pathways, human actions and various disruptive events that must, as a minimum, be considered by the implementer. In most other countries, the choice of stylised situations and critical groups is considered a matter for the implementer, or for dialogue between the implementer and the regulator. In general, human nutritional needs and metabolism of the present day are assumed to continue in the future, and speculation about advances in science and technology is excluded. The doses and risks calculated for critical groups in stylised situations are not to be interpreted as measures of expected health detriments and risks to actual future individuals. Rather they are to be interpreted as stylised indicators of potential detriment, i.e. illustrations of potential detriment to a stylised, hypothetical individual based on agreed sets of assumptions. This needs to be stressed in the presentation of safety assessment results.

4.4 Scenarios for the long-term evolution of the geological environment

At times sufficiently far into the future, a wide range of scenarios for geological evolution can be envisaged, some of which could have far-reaching implications for the repository. The possibility that a repository might ultimately become exposed at the surface by uplift and erosion may, for example, need to be considered. Some regulations, including those that require calculations of dose and risk to be carried out at least until the time that these safety indicators attain their maximum, can lead to calculations being continued to times when the evolution of the geological environment cannot be predicted with confidence, even for a well-chosen, stable site. If in practice these calculations involve the assumption of a stable geological environment, as is usually the case, less weight should be attached to arguments based on the results at times when the assumption of stability becomes questionable. As discussed further below, arguments related to the substantially reduced hazard associated with the waste at these times can play a role, although it may not be

3. IAEA BIOMASS: BIOsphere Modelling and ASSessment (BIOMASS) of the International Atomic Energy Agency (IAEA).

reasonable to discount hazard entirely and additional arguments for safety may still need to be sought.

A suggestion from the timescales workshop was to explore the possibility of using a stylised approach similar to that adopted to address uncertainties in the evolution of the surface environment and the nature of future human actions. This would avoid speculation regarding geological evolution at times when the hazard associated with the waste is greatly reduced compared to that at the time of emplacement, although the acceptability of such an approach from the regulatory point of view would need clarification. Currently, most regulations provide guidance neither for the range of possibilities or scenarios for geological evolution that safety assessments should explore at these distant times, nor for the weight that should be attached to the results of dose or risk calculations, compared to other perhaps more qualitative arguments for safety. Some guidance of this type might certainly be useful, and there is currently a trend in this direction (see Section 4.6).

4.5 Complementary safety and performance indicators

The use of dose and risk as primary safety indicators does not preclude the use of other additional indicators of safety or performance. Two broad categories of indicators can be distinguished. One category includes the *in situ* observations and measurements that can provide evidence for the favourable characteristics of the repository and its surroundings, such as groundwater ages and observations of immobility of naturally occurring uranium and thorium in certain geological formations, as discussed in Section 4.1. The other includes indicators that are calculated by means of safety assessment models, including dose and risk themselves, but also such complementary indicators as concentrations, fluxes and inventories of activity or radiotoxicity. The following discussion relates to this second category of indicator.

The presentation of dose or risk as a function of time is not, on its own, an effective way to convey the message that deep geological repositories provide an appropriate level of safety. For example, it tends to focus attention on the small releases that may eventually occur, rather than on the fact that most radioactivity is isolated and contained within the repository and its immediate surroundings, where it decays. It can thus be useful to complement graphs of dose or risk as functions of time with additional graphs or tables giving indicators that more directly illustrate the performance of the different repository barriers and combinations of barriers. The European SPIN project [22, 23] concluded that several performance indicators can be used to show different aspects of the functioning of the individual compartments of the multi-barrier system. Such indicators are, e.g., the time-dependent inventories in and fluxes from the compartments of the system, which show where the radioactivity is and how it moves inside the system at any particular time.

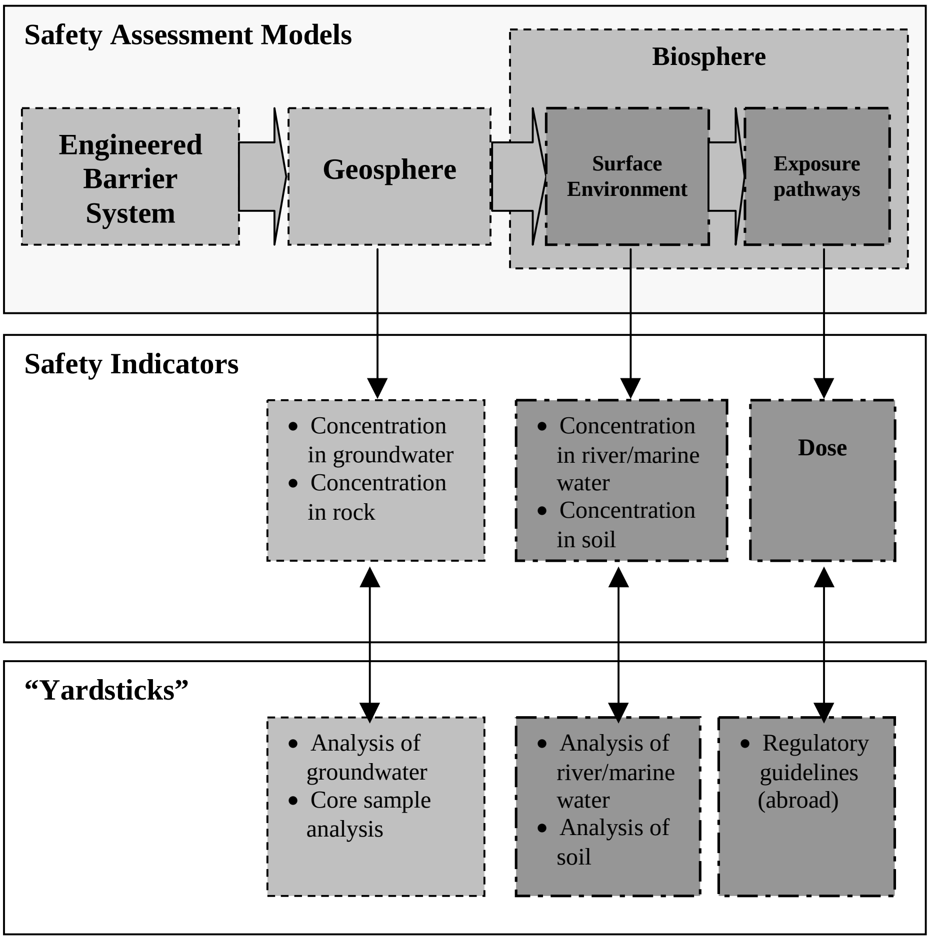
In addition, as discussed below, complementary indicators can help avoid both the limited predictability of the surface environment and, on a far longer timescale, the limited predictability of the geological environment, and provide useful additional arguments for safety if accepted reference values or yardsticks for comparison can be derived. The choice of indicators can be strongly dependent not only on the timescale under consideration, but also on the context of the assessment in question – e.g. the specific geographical and geological setting and the regulatory context. The use of complementary indicators in the Japanese H12 safety assessment is illustrated in Box 4.

Possible starting points for the definition of reference values are considerations of either acceptable hazard (as for dose and risk) or negligible disturbance of nature – e.g. disturbances to the fluxes or concentrations of naturally occurring radionuclides that take place within natural systems. There are, however, some problems concerning:

- the temporal and spatial scale at which observations of natural systems need to be made – different reference values might, for example, be obtained by averaging over local or more regional scales;
- the fact that natural conditions are not necessarily "harmless"; and
- how to deal with radionuclides that are not found in nature.

Guidance concerning the advantages, disadvantages and limitations of indicators complementary to dose and risk is available in several documents at national and international levels [22-26]. The European SPIN project [23] identified and assessed a range of complementary indicators. Box 5 summarises conclusions from the SPIN project concerning the advantages, disadvantages and possible usage of effective dose rate as an indicator, and also two complementary indicators were found to provide significant benefits, particularly over longer timescales.

Box 4. **Assessment models, complementary safety indicators and the corresponding reference values or “yardsticks” used in the H12 safety assessment [26]**



Two specific complementary indicators are discussed here in more detail, although others were also discussed at the timescales workshop. These are (i), the radiological toxicity of the waste, which can provide a safety indicator that can be evaluated without presupposing a stable geological environment, and (ii), the release rates of radionuclides to the surface environment, which can, in some cases, provide a safety indicator that can be evaluated without the need for detailed assumptions regarding the future state of this environment.

Box 5. Conclusions from the SPIN project concerning the advantages, disadvantages and possible usage of effective dose rate as an indicator, and also two complementary indicators were found to provide significant benefits [23]

Effective dose rate

Advantages:

The basic indicator used to determine the safety of nuclear practices worldwide
Based on the best safety-relevant weighting scheme for the present biosphere
Reference values are defined in national regulations

Disadvantages:

The uncertainties of the biosphere pathways and aquifer dilution are included

Conclusion:

The indicator is useful for all time frames, but should be given a higher preference for early time frames. The higher preference for early time frames is due to the uncertainties of the biosphere pathways which increase with time

Radiotoxicity concentration in biosphere water

Advantages:

A safety-relevant weighting scheme is available in form of ingestion dose coefficients provided by ICRP

The uncertainties of biosphere pathways are excluded

Safety-relevant reference values can be developed

Disadvantages:

The uncertainties of the aquifer dilution are included

Conclusion:

The indicator is useful for all time frames, but a higher preference for early and medium time frames should be given. Because the uncertainties relating to aquifer dilution increases with time this indicator is less relevant for late time frames

Radiotoxicity flux from geosphere

Advantages:

A safety-relevant weighting scheme is available in form of ingestion dose coefficients provided by ICRP
The uncertainties of biosphere pathways and aquifer dilution are excluded
Safety-relevant reference values can be developed

Disadvantages:

Reference values can not be established by measurement only; they must be obtained using models, thus introducing another type of uncertainty

Conclusion:

The indicator is useful for all time frames, but a higher preference for late time frames should be given. The higher preference for late time frames is because the uncertainties relating to biosphere pathways and also aquifer dilution, which increase with time, are excluded. The process of establishing a reference value for this indicator is complicated by the fact that fluxes can not be measured directly but are derived from measured concentrations and assumptions about the relevant hydrogeological setting.

The radiological toxicity of the waste

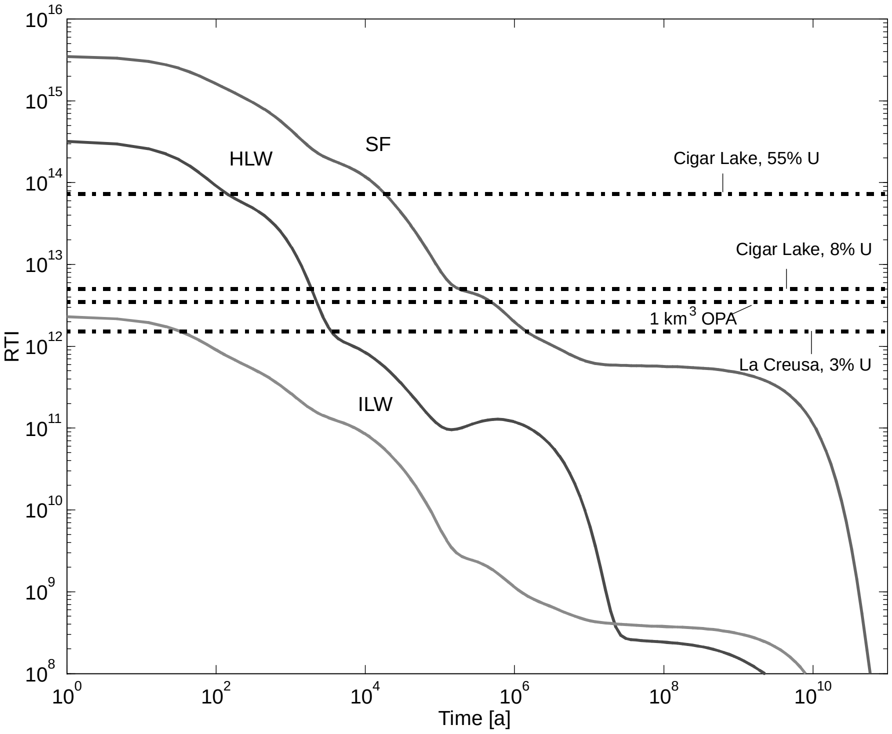
No universally agreed definition of radiological toxicity exists, but it can, for example, be loosely defined as the hypothetical dose resulting from ingestion of the radioactive material. The radiotoxicity of the waste provides an indicator that can serve two distinct roles in a safety case.

- At times when geological stability can be assured, it can usefully illustrate the rationale behind the strategy of isolating and containing the waste while radioactive decay reduces the associated hazard. In spite of the limits of predictability discussed earlier, the methods of geological sciences are generally adequate to show, for a suitably chosen site, that the waste will be isolated in a repository for a sufficient time for its radiological toxicity to decrease substantially.
- At later times when the geological stability of the site can no longer be assumed and less weight is attached to the results of dose and risk calculations, radiological toxicity gives an indication of the residual hazard posed by the waste and provides a safety indicator that can complement dose and risk if accepted reference values or yardsticks for comparison can be derived.

This second role is consistent with a general trend towards a shift in the emphasis or weight away from calculations of individual dose or risk and towards alternative, sometimes more qualitative, arguments and the use of complementary safety and performance indicators when judging compliance on longer timescales. This is increasingly being reflected in regulations, as discussed in a later section (see Box 8).

Possible reference values or criteria with which this indicator can be compared are provided by natural systems, such as uranium ores. It has been shown, for example, that after about 100 000 years the radiological toxicity of one tonne of Swedish spent fuel is on a par with the radiological toxicity of the natural uranium from which it was derived. In the Swiss assessment of a repository in Opalinus Clay, Nagra has compared the radiological toxicity of the waste with that of the natural radionuclides contained in 1 km^3 of Opalinus Clay as well as that of a volume of natural uranium ore corresponding to the volume of the spent fuel (SF)/high level waste (HLW) emplacement tunnels, and used this to argue that one million years is the period of principal concern (Box 6).

Box 6. **Radiotoxicity index (RTI) of spent fuel (SF), vitrified high-level waste (HLW) and long-lived intermediate-level waste (ILW) as functions of time, together with some reference levels [14]**



The radiotoxicity index is defined as the hypothetical dose resulting from the ingestion of radioactive material, made dimensionless by dividing it by a reference dose – in this case the 0.1 mSv derived from the annual dose limit given in the Swiss regulatory guideline. The reference levels correspond to the SF/HLW tunnels hypothetically filled with natural uranium ore of different grades. The RTI of 1 km^3 of Opalinus Clay (OPA) is also shown. At times beyond one million years, the radiotoxicity of even the most toxic waste (SF) drops below these reference levels.

The limitations of safety arguments based on the radiological toxicity of the emplaced waste should, however, be noted. As illustrated by the examples above, different comparisons can lead to different crossover times, thus potentially limiting the applicability of this type of argument. Furthermore, activity or toxicity curves alone have limited meaning from the point of view of risk and safety, since, for example, the mobility of radionuclides is not taken into account. Even when a plot suggests that the repository has become comparable to a natural system in certain important aspects, this does not necessarily indicate a return to unconditionally safe conditions. Nevertheless, in spite of these reservations, radiological toxicity and comparison with natural systems such as uranium ores offer a basis for a safety indicator that can usefully complement dose and risk.

Release rates of radioactive substances

As noted in Section 3, the deep geological environment is often effectively buffered or protected from changes in the surface environment, although, in a few cases, changes at or near the surface can have some influence on, for example, the rates and pattern of groundwater movement. This protection means that the release rates of radionuclides to the surface environment provide indicators that can be evaluated without reference to the often poorly predictable conditions at or near the surface, being determined principally by the relatively predictable evolution of the repository and its surroundings.

The release rates of radioactive substances to the surface environment have been used as safety or performance indicators in several recent safety assessments. In Finland, the regulator considers that the nature of the surface environment is so uncertain beyond about ten thousand years (a period termed the "era of extreme climate changes" by the Finnish regulator, see Box 8) that it is prudent to base radiation protection criteria on constraints for release rates of individual radionuclides to the surface environment, rather than on dose or risk constraints. In general, however, dose or risk based radiation protection criteria are specified by regulators and the role of additional indicators is to complement, but not to supersede, arguments for safety based on dose and risk.

Arguments based on complementary indicators such as these might sometimes be more accessible to a non-specialist audience than those based primarily on dose or risk calculations. Such arguments still, however, require careful explanation; neither the indicators themselves (including dose and risk), nor the yardsticks with which they are compared are self-explanatory. Confusion may also be caused when, in presenting the safety case, discussion switches from one indicator to another at different times. A sound strategy regarding the choice and utilisation of indicators thus needs to be developed and communicated.

The use of complementary indicators, as well as reference values for comparison, is an issue that may well deserve further regulatory guidance. In the early stages of a project, regulations should perhaps give general guidance on the provision of complementary information by the implementer, rather than prescribe the use of specific complementary indicators. Only when regulations are not generic, but instead concern a specific case, site or concept (as in the Finnish case), and after detailed studies have shown the relevance and applicability of reference values, might regulations usefully give requirements relating to specific complementary indicators.

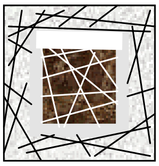
4.6 The emphasis placed on different lines of argument at different times or in different time frames

In a safety case, emphasis at any given time in the evolution of the repository and its environment is placed on those safety functions that are expected to be most effective, and on those arguments that are considered the most convincing. For example, canisters may initially be confidently expected to provide complete containment of the wastes and safety arguments may emphasise evidence supporting the integrity of the canisters over a certain period. At later times, complete containment cannot be relied upon, and arguments based, for example, on the stability of the waste forms, geochemical immobilisation, the slow rate of groundwater movement and the stability of the geological environment, are used to show that releases to the human environment are nevertheless small. Although not necessarily emphasised in a safety case, these latter arguments also provide additional assurance of safety at times when the canisters are expected to be intact – i.e. even if the longevity of the containers or canisters is less than expected, other mechanisms exist that nevertheless ensure adequate levels of safety. This is an example of the multi-barrier or multi-function concept (e.g. [14] [15]).

In some safety assessments, discrete periods or "time frames" are defined [3] in which different lines of argument are available (Box 7). Time frames can provide a useful framework for internal discussions among experts within an implementing organisation, between implementers and regulators and between implementers, regulators and the public. Some regulations imply or even explicitly define the arguments to be used in different time frames, and it would certainly be useful if regulations were to provide further guidance and clarification on issues related to the weighting of arguments, including how exactly weighting should be defined.

Box 7. **Illustration of the presentation of a safety assessment based on five time frames**

The figure provides an illustration of what is currently envisaged in terms of the assessment and presentation of each of the proposed five time frames in the planned update to the Nirex generic post-closure performance assessment (GPA).



Time frame 1: Waste containers as emplaced

- Institutional control and monitoring (may include long-term storage period)
- Physical barrier intact, containment of radionuclides
- Repository starting to resaturate
- Releases limited to minor diffusive releases through vents and gaseous

Key Performance Indicators:

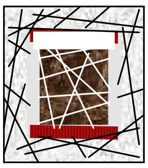
- Decrease in redionuclide inventory
- Zero flux from near field
- Gaseous releases

Confidence arguments:

- Steel corrosion measurements
- Decay of short-lived radionuclides

Modelling approaches:

- Decay within packages
- Gas generation and Transport



Time frame 2: Physical and chemical barriers evolving

- Repository fully saturated
- Physical barrier may start to break down but waste form limits mobility
- Many radionuclides relatively insoluble, greatest release by diffusion
- Degradation of organics producing complexants
- Gas generation and migration

Key Performance Indicators:

- Decrease in inventory
- Flux from near field
- Gaseous releases

Confidence arguments:

- Comparisons with corrosion of Roman nails
- Cement analogues

Modelling approaches:

- Package-scale model
- Near-field chemistry

Time frame 3: Chemical barrier

- Reducing conditions in near field fully established
- Corrosion causes failure of significant number of packages
- Advective-diffusive release of radionuclides, particularly those which are poorly sorbed
- Gas generation and migration

Key Performance Indicators:

- Flux from near field
- Gaseous releases

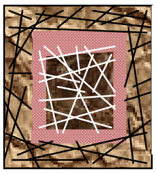
Confidence arguments:

- Cement analogues
- Maqarin site – limited movement
- of radionuclides away from repository

Modelling approaches:

- Repository-scale near-field model
- Steady-state, regional-scale
- groundwater flow

Box 7. **Illustration of the presentation of a safety assessment based on five time frames** (cont'd)



Time frame 4: Stable geological barrier

- Most waste packages have failed, offering little resistance to radionuclide migration, therefore the near field is treated as homogeneous
- Migration of radionuclides from near field through far field

Key Performance Indicators

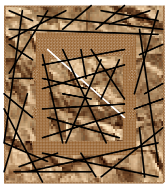
- Fluxes out of near and far field
- Radiological risk
- Environmental effects
- Comparisons with natural fluxes

Confidence arguments:

- Maqarin site – limited migration
- Oklo – retardation
- Palaeohydrogeology – geosphere stability

Modelling approaches:

- Homogeneous near-field 'soup' model
- Groundwater transport models



Time frame 5: System responding to external change

- Homogeneous near field
- Migration of radionuclides from near field through far field
- Need to consider climate change and hydrogeological changes
- Releases to different climate states

Key Performance Indicators

- Radiological dose or risk
- Comparison with background radiation levels

Confidence arguments:

- Comparisons with natural radiation levels

Modelling approaches:

- Homogeneous near-field 'soup' model
- Reference geosphere
- Reference biospheres representing different climate states

There is currently no general consensus as to how exactly time frames should be defined and how weights or emphasis should be assigned to different arguments in different time frames. Indeed, the issues involved are generally programme-, concept- and site-specific, although similarities do exist between different countries in the reasoning used to delineate time frames (see Box 8), which is generally based on scientific understanding of the evolution of the repository and its environment. There is, furthermore, an increasing recognition that the presentation of the safety case needs to be tailored to address the concerns of the intended audience and this can influence the weighting placed on particular arguments in different time frames, as discussed in the context of public concerns in the following section.

Box 8. **Time frames in regulations**

Regulations in the United Kingdom (see [6]) imply a time frame in which detailed calculations of risk and dose are appropriate and a more distant time frame in which simpler scoping calculations and supporting qualitative information are more appropriate, when the validity of models of radionuclide release and transport becomes questionable. In Sweden, a risk limit is set without any time limitation. Quantitative analyses of the impact on human health and the environment are, however required only for the first thousand years, whereas, in the subsequent period, the requirements are less well defined and the objective becomes to assess the protective capability of the repository system based on various possible scenarios. The Finnish regulator [10] is more precise in its requirements, explicitly defining the following post-closure time frames for safety assessments for spent fuel:

- the "environmentally predictable future" (several thousand years), during which conservative estimates of dose must be made;
- the "era of extreme climate changes" (beyond about ten thousand years) when periods of permafrost and glaciation are expected, radiation protection criteria are based on geo-bio flux constraints; and
- the "farthest future" (beyond about two hundred thousand years), when the activity in spent fuel becomes less than that in the natural uranium from which the fuel was fabricated, for which no rigorous quantitative safety assessments are required and statements regarding safety can be based on more qualitative considerations.

In one of the papers presented at the *timescales workshop* [27], in order to balance ethical and technical considerations and public concerns, a series of time-graded containment objectives is suggested with two target times.

- It is suggested that the initial period of 500 years corresponds to the period of greatest public concern. For this period the objective of total containment is proposed, at least for spent fuel and reprocessed high-level waste in view of the high hazard. This period may overlap with a period of monitoring during which a repository is kept open and unsaturated: in many national programmes, there are proposals for an extended period of monitored, retrievable underground storage. The period may also coincide, at least to some extent, with a phase of relatively complex transient phenomena, including resaturation of the repository and its surroundings. If complete containment can be assured during the transient phase, this can reduce the need to model these phenomena in detail, although the implications of transient phenomena on the longer-term characteristics of the disposal system must be considered.

- In the time period up to 100 000 years – the end point roughly corresponding to the crossover point on activity curves – a dose constraint derived from natural background radiation levels is prescribed.
- Beyond some 100 000 years, the proposed objective is that the eventual redistribution of the residual activity by natural processes remains indistinguishable from natural regional variations in radiation levels.

5. HOW CAN PUBLIC CONCERNS AFFECT THE EMPHASIS GIVEN TO DIFFERENT LINES OF ARGUMENT AT DIFFERENT TIMES?

A safety case often needs to address not just the concerns of technical specialists, but also those of the wider public. Indeed, decisions regarding whether, when and how to implement geological disposal are likely to require thorough public examination and the involvement of all relevant stakeholders.

Safety cases need to be presented to the public in an understandable manner and documents aimed at the public should focus on arguments that can be understood without reference to detailed technical analyses. This can influence the time frames that receive the most emphasis and the safety functions and lines of argument that are stressed in documents and other presentational materials aimed at the public. For example, an emphasis on arguments based on direct observation (e.g. the stability of natural uranium deposits), and on indicators that allow the performance of the disposal system to be placed in perspective with natural phenomena and current natural conditions (e.g. natural radioactivity fluxes), might be appropriate in documents intended for a wide, non-specialist audience.

The long timescales addressed in safety assessments are perhaps unfamiliar to the public, and statements made for such periods could be met with some scepticism. They are orders of magnitude greater than the timescales of direct human experience, and may appear to stretch scientific knowledge significantly, particularly given the occasional failure to predict (sometimes with catastrophic consequences) the behaviour of engineered structures in the much shorter term, at least in the absence of adequate maintenance. There is also an apparent gap between the times that matter to most people and those invoked in repository safety studies. To the layman, long-term typically means several decades – i.e. a few generations.

The first few hundred years following emplacement of the waste is probably the period of highest concern to many members of the public (see, for example, the experience from public hearings and other discussions with stakeholders in connection with the licensing procedure for Konrad, Germany [28], as well as EC's RISCOM-2 project[4]) and could possibly be emphasised to a greater degree when safety cases are presented to the public. Generally, zero release is expected during the earlier period, and this point could be better argued in many safety cases. Monitoring in the operational and immediate post-closure period may potentially contribute to public confidence.

In general, arguments relevant to very long timescales may be of less interest to the public. The public is, however, heterogeneous and public interest in longer timescales should not be discounted. Indeed, on several occasions, members of the public have shown a strong interest in events and situations that are expected to occur only in the distant future. In Sweden and Finland, for example, the effects of glaciation on a repository have provoked a particular public interest.

4. RISCOM-2 project: Project of the European Commission concerning transparency in risk assessment.

6. KEY MESSAGES

a) The timescales over which a safety case needs to be made

The long timescales addressed in safety assessments arise from the long half lives of some of the isotopes in the waste and the high degree of effectiveness with which deep geological disposal facilities are expected to contain radioactivity – safety studies for deep geological repositories tend to focus on the distant times when releases eventually occur. There are no ethical arguments that justify imposing a definite limit to the period addressed by safety assessments, in spite of the technical difficulties that this can present to those conducting such assessments. It is an ethical principle that the level of protection for humans and the environment that is applicable today should also be afforded to humans and the environment in the future, and this implies that the safety implications of a repository need to be assessed for as long as the waste presents a hazard. In view of the way in which uncertainties generally increase with time, or simply for practical reasons, some cut-off time is inevitably applied to calculations of dose or risk. There is, however, generally no cut-off time for the period to be addressed *in some way* in safety assessment, which is seen as a wider activity involving the development of a range of arguments for safety.

b) The limits to the predictability of the repository and its environment

In order to maintain credibility within the scientific community as well as with other stakeholders, it is important to acknowledge the limits of predictability of the repository and its environment in both regulations and in safety cases. Well-supported statements regarding the radiological consequences can be made that cover a prolonged period provided a repository is well designed and a suitable, geologically stable site is selected. At times when the stability of the geological environment can no longer be assured, a more qualitative assessment of radiological consequences is likely to be adequate, because of the strongly decreased radiological toxicity of the waste that is expected at these times.

c) Arguments for safety in different time frames

Multiple lines of argument are useful for building a convincing safety case. Some lines of argument are more qualitative in nature than others, and there may be an emphasis on different types of argument and different indicators of performance and safety in different time frames. Safety assessments are increasingly taking into account the full range of arguments for safety that is available, as well as the safety and performance indicators that can be used to complement dose and risk, and regulations are increasingly providing guidance regarding their use. When discussing different time frames, it is important to bear in mind the decrease with time of the hazard presented by the waste.

d) Stylised approaches

Given that changes in human society, technology and the surface environment are likely, and are largely unpredictable over the time period of interest in safety assessments, there is international consensus that radiological doses and risks calculated for hypothetical human groups dwelling in the future, but with habits and technology similar to that of the present day, are appropriate as indicators of repository safety. The doses and risks calculated for critical groups in stylised situations are not to be interpreted as measures of expected health detriments and risks to actual future individuals. Rather they are to be interpreted as stylised indicators of potential detriment, i.e. illustrations of potential detriment to a stylised, hypothetical individual based on agreed sets of assumptions. This needs to be stressed in the presentation of safety assessment results. Adoption of a stylised approach avoids open-ended speculation on issues such as future human habits for which uncertainties are large and irreducible.

e) Complementary safety and performance indicators

The use of safety and performance indicators other than dose and risk can give indications of safety independent of both the limited predictability of the surface environment and, on a far longer timescale, the limited predictability of the geological environment. They provide useful complementary arguments for safety if accepted reference values or criteria for comparison can be agreed upon. Possible starting points for the definition of reference values are considerations of either acceptable hazard (as for dose and risk) or negligible disturbance of nature. There are, however, some problems concerning (1) the temporal and spatial scale at which observations of natural systems need to be made, (2) the fact that natural conditions are not necessarily "harmless", and (3) how to deal with radionuclides that are not found in nature. Arguments based on complementary indicators require careful explanation and a sound strategy regarding the choice and utilisation of indicators needs to be developed and communicated. The use of complementary indicators, their weighting in different time frames, as well as reference values for comparison, are issues that may well deserve further regulatory guidance.

f) Addressing public concerns

Documents aimed at the public should focus on arguments that can be understood without reference to detailed technical analyses for all timescales that are addressed. The presentation of safety cases for the period of a few hundred years following emplacement of the waste may, however, deserve particular attention, with greater emphasis in documents aimed at the public on the fact that, for most repository concepts, zero release of radioactivity is expected in this period. Monitoring in the operational and immediate post-closure period may potentially contribute to public confidence.

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ACRONYMS

Andra	National Agency for Radioactive Waste Management, France
DGSNR	Direction Générale de la Sûreté Nucléaire et de la Radioprotection
FSC	Forum Stakeholder Committee
GRS	Gesellschaft fuer Anlagen und Reaktorsicherheit
HLW	High-level Waste
HSK	Swiss Federal Nuclear Safety Inspectorate
ILW	Intermediate Level Waste
IAEA	International Atomic Energy Agency, Vienna, Austria
IGSC	Integration Group for the Safety Case
IRSN	French Institute for Radiological Protection and Nuclear Safety
Nagra	National Cooperative for the Disposal of Radioactive Waste, Switzerland
NEA	Nuclear Energy Agency
Nirex	United Kingdom Nirex Limited
NUMO	Nuclear Waste Management Organization of Japan
ONDRAF/NIRAS	National Organization for Radioactive Waste and Fissile Materials, Belgium
SAM Ltd	Safety Assessment Management Ltd
SF	Spent Fuel
US-DOE-YM	Department of Energy, Yucca Mountain, USA
US-EPA	U.S. Environmental Protection Agency

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