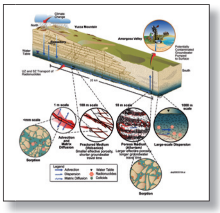
Radioactive Waste Management
2009

Considering Timescales in the Post-closure Safety of Geological Disposal of Radioactive Waste



NUCLEAR ENERGY AGENCY

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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FOREWORD

A key challenge in the development of safety cases for the deep geological disposal of radioactive waste is handling the long time frame over which the radioactive waste remains hazardous. The intrinsic hazard of the waste decreases with time, but some hazard remains for extremely long periods. Safety cases for geological disposal typically address performance and protection for thousands to millions of years into the future. Over such periods, a wide range of events and processes operating over many different timescales may impact a repository and its environment. Uncertainties in the predictability of such factors increase with time, which makes it increasingly difficult to provide definite assurances of performance and protection over longer timescales. Thus, timescales, the level of protection and the assurance of safety are all linked.

The handling of issues related to timescales was discussed at an OECD Nuclear Energy Agency (NEA) workshop held in Paris in 2002. A report providing an account of the lessons learnt and the issues raised at the workshop was published in 2004. There is, however, an evolving understanding regarding the nature of the issues related to timescales and how they should be addressed, which provided the motivation for preparing the present report. This report is based on the analysis of the responses to a questionnaire from 13 NEA member countries, as well as discussions that took place in several subsequent meetings.

The approaches to handling timescales for geological disposal of radioactive waste are influenced by ethical principles, the evolution of the hazard over time, uncertainties in the evolution of the disposal system (and how these uncertainties themselves evolve) and the stability and predictability of the geological environment. Conversely, the approach to handling timescales can affect aspects of repository planning and implementation, including regulatory requirements, siting decisions, repository design, development and presentation of safety cases, and the planning of pre- and post-closure institutional controls such as monitoring requirements. This is an area still under discussion among NEA member countries.

This report reviews the current status of discussions and approaches in waste management programmes to address various timescales of relevance for geological disposal of radioactive waste. A comparison of current findings with those from the 2002 workshop has reinforced key findings, including that:

- limits to predictability concerning the evolution of behaviour of the repository and its environment need to be acknowledged in safety cases;
- doses and risks evaluated in safety assessments must be interpreted as illustrations of potential impact to stylised, hypothetical individuals;
- arguments complementary to dose and risk are necessary, especially at timescales beyond which quantitative safety assessments can be supported;
- the period of a few hundred years following emplacement of the waste may deserve particular attention in information aimed at the general public.

The present report shows that since 2002 there has been an evolution of views regarding certain aspects. For example, the report highlights developments to partition safety cases into discrete future time periods and developments in phenomenological and functional analysis over different time frames. There is growing use of indicators – both qualitative and quantitative – other than dose and risk, although the interpretation and weighting for different time frames is an aspect that merits further attention. In terms of ethical obligations to future generations, there is acknowledgement that different and sometimes competing ethical principles need to be balanced; how to achieve this balance is an issue still under discussion in many programmes.

The various methods and approaches discussed in this report demonstrate that a range of approaches are now available that can be applied for presenting and developing safety cases to address various timescales. Furthermore, there is room to development these approaches. In many programmes, a significant part of the responsibility for the handling of timescales in safety cases lies with the agency implementing waste disposal. However, parts of this task may also be established or guided by regulatory requirements. Wherever the final responsibility lies, a dialogue between the implementer, the regulator and other stakeholders is valuable in resolving the issues in a manner that is widely accepted. Such dialogue is ongoing in many programmes.

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EXECUTIVE SUMMARY

A key challenge in the development of safety cases for geological repositories is associated with the long periods of time over which radioactive wastes that are disposed of in repositories remain hazardous. Over such periods, a wide range of events and processes characterised by many different timescales acts on a repository and its environment. These events and processes, their attendant uncertainties, and their possible impacts on repository evolution and performance must be identified, assessed and communicated in a safety case.

The handling of issues related to timescales was discussed at an OECD/NEA[1] workshop held in Paris in 2002 and a short report providing an account of the lessons learnt and issues raised at the workshop, was published in 2004 (NEA, 2004a). There is, however, an evolving understanding regarding the nature of the issues related to timescales and how they should be addressed, which provides the motivation for the present report. The report is based on the analysis of the responses to a questionnaire received from twenty-four organisations, representing both implementers and regulators from thirteen OECD member countries, as well as discussions that took place in several later meetings.

The report is aimed at interested parties that already have some detailed background knowledge of safety assessment methodologies and safety cases, including safety assessment practitioners and regulators, project managers and scientific specialists in relevant disciplines. Its aims are:

- to review the current status and ongoing discussions on the handling of issues related to timescales in the deep geological disposal of long-lived radioactive waste;
- to highlight areas of consensus and points of difference between national programmes; and
- to determine if there is room for further improvement in methodologies to handle these issues in safety assessment and in building and presenting safety cases.

The handling of issues related to timescales in safety cases is affected by a number of general considerations, which are described first. Three broad areas in the regulation and practice of repository planning and implementation affected by timescales issues are then discussed:

- repository siting and design and the levels of protection required in regulation;
- the planning of pre- and post-closure actions; and
- developing and presenting a safety case.

Finally, a synthesis of findings is made, including a review of the statements made in the 2004 "lessons learnt" report in light of the discussions contained in the present report. Many of the issues treated in the course of the project are subject to various interpretations, and remain under discussion in national programmes, as well as internationally. Therefore, the findings in this report should not be

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[1] The Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD).

viewed as conclusive, but rather as a contribution in moving ahead the debate and understanding the similarities and differences among approaches in national programmes.

General considerations in the handling of issues of timescales

Ethical principles

Given the long timescales over which radioactive waste presents a hazard, decisions taken by humans now and in the near future regarding the management of the waste can have implications for the risks to which generations in the far future may be exposed. There are thus ethical issues to be considered concerning, for example, our duty of care to future generations and the levels of protection that should be provided. Decisions regarding the phased planning and implementation of repositories, particularly whether to close a repository at the earliest practical time or to plan for an extended open period, also have an ethical dimension. This is because they affect the flexibility allowed to future generations in their own decision making as well as the burden of responsibility passed to these generations. Relevant ethical principles, such as inter-generational and intra-generational equity and sustainability, are open to different interpretations and can sometimes compete. The interpretations made and balance struck between competing principles is a matter of judgement and may vary between different countries and stakeholder groups, and remain matters of discussion internationally, e.g. in the Long-term Safety Criteria (LTSC) Task group of the NEA Radioactive Waste Management Committee (RWMC).

Evolution of hazard

The hazard associated with radioactive waste results primarily from the external and internal radiation doses that could arise in the absence of adequate isolation (including shielding) and containment of the waste. Although the radioactivity of the waste declines significantly with time, the presence of very long-lived radionuclides means that the waste may continue to present some level of hazard for extremely long times.

Uncertainty in the evolution of the repository system

Geological repositories are sited and designed to provide protection of man and the environment from the hazard associated with long-lived radioactive waste by containing and isolating the waste. Though the sites and engineered barrier designs are generally chosen for their long-term stability and predictability, repository evolution is nonetheless subject to unavoidable uncertainties that generally increase with time. Furthermore, radiological exposure modes, which are closely related to individual human habits, can be predicted with confidence only in the very short term. The decreasing demands on system performance as a result of the decreasing hazard of the waste partly offset the increasing demands that uncertainties place on safety assessment. Nevertheless, while some hazard may remain for extremely long times, increasing uncertainties mean that there are practical limitations as to how long anything meaningful can be said about the protection provided by any system against the hazard. These limitations should be acknowledged in safety cases.

Stability and predictability of the geological environment

Repository sites are chosen for their geologically stability and broad predictability. Although predictions of the evolution of even the most stable sites become uncertain over long enough timescales, many national programmes have identified sites that are believed to be stable and sufficiently predictable over timescales of millions of years or more, based on an understanding of their geological histories over still longer timescales. Others plan to search for such sites. For example, in Germany, any new site selection process is likely to follow the procedure set out by an interdisciplinary expert group (Arbeitskreis Auswahlverfahren Endlagerstandorte – AkEnd), which requires the identification of a site having an "isolating rock zone" that will remain intact for at least a million years, based on the normal evolution of the site.

Repository siting and design and the levels of protection required in regulation

In repository siting and in designing complementary engineered barriers, the robustness of the system is a key consideration. Thus, events and processes that could be detrimental to isolation and containment, as well as sources of uncertainty that would hamper the evaluation of repository evolution and performance over relevant timescales, are, as far as reasonably possible, avoided or reduced in magnitude, likelihood or impact.

The isolation of the waste from humans is regarded as an essential role of the geological environment, and must be considered at all times addressed in a safety case. On the other hand, both the geological environment and the engineered barriers can contribute to ensuring that radionuclides are substantially contained, and the roles of the different system components in this regard can vary as a function of time. Most programmes aim for containment of the major part of the radionuclide inventory at least within a few metres from the emplacement horizon and certainly containment in the geological stratum or immediate rock mass where the repository is located, although, in some disposal concepts, more mobile radionuclides, such as ^{36}Cl and ^{129}I, are expected to migrate relatively rapidly (in terms of geological timescales) if released from the repository. The consequences of these and any other releases need to be evaluated.

Regulations specify what needs to be shown, and in some cases over what time frames, in order that a proposed site and design can be considered to offer acceptable levels of protection from this hazard.

The minimum levels of radiological protection required in the regulation of nuclear facilities are usually expressed in terms of quantitative dose or risk criteria. In the case of geological repositories, quantitative criteria apply over time frames of at least 1 000 or 10 000 years and sometimes without time limit. It is, however, recognised in regulations and safety cases that the actual levels of dose and risk, if any, to which future generations are exposed cannot be forecast with certainty over such time frames. Models are used that include certain stylised assumptions, e.g. regarding the biosphere and human lifestyle or actions. Additionally, the "dose" that is being calculated is what radio-protectionists refer to as "potential dose". Hence, the calculated values are to be regarded not as predictions but rather as indicators that are used to test the capability of the system to provide isolation of the waste and containment of radionuclides.

The concept of "constrained optimisation" put forth by the International Commission for Radiological Protection (ICRP) in ICRP-81 is also often a requirement; it is reflected in various terminology but encompasses the concepts in ICRP-81 that a series of technical and managerial principles, such as sound engineering practice and a comprehensive quality assurance programme are key elements to enhance confidence in long-term safety. For geological repositories, optimisation is generally considered satisfied if all design and implementation decisions have been taken with a view to ensuring robust safety both during operations and after repository closure and if provisions to reduce the possibility and impact from human intrusion have been implemented. In some regulations, alternative or complementary lines of evidence for protection and other more qualitative considerations are required or given more weight beyond 1 000 or 10 000 years, in recognition of the fact that increasing uncertainties may make calculated dose or risk less meaningful.

Generally, although the measures of protection specified in regulations may vary with time, this does not necessarily reflect a view that it is acceptable to expose future generations to levels of dose or risk different to (and higher than) those that are acceptable today. Rather, it reflects practical and technical limitations: in particular, regarding the weight that can be given to results of calculations over such long time frames and the meaning of dose estimates at times when even human evolutionary changes are possible. There is ongoing discussion on the issue of how to define and judge criteria for protection in the furthest future, as a basis for decision making today [see e.g. work by the RWMC Regulator's Forum,(NEA, 2007)].

National policies in the planning of pre- and post-closure actions

Current national programmes vary considerably in the degree to which an extended open period prior to the complete backfilling and closure of a repository is foreseen. The ethical principle that future generations should be allowed flexibility in their decision making favours assigning to future generations the decisions regarding backfilling and closure. Early backfilling and closure may, on the other hand, be seen as more consistent with the ethical principle that undue burdens should not be passed on to future generations, and also guards against the possibility of future societal changes, which could lead to lapses in the necessary maintenance and security. Another concern, particularly for repositories in saturated environments, is that detrimental changes to the system may occur or events take place during the open period, and that the severity of these changes or events will increase with the duration of the open period. In such cases, it may be prudent to work towards closure soon after completion of waste disposal. It is, however, recognised that such technical considerations need to be balanced against other factors, such as policies on monitoring and retrievability, which may require a more prolonged open period, or the views of the local community. In any case, it is widely agreed that flexibility regarding the open period should not extend so long as to jeopardise long-term safety.

Monitoring of a wide range of parameters within and around a repository is likely to be carried out prior to repository closure, and some monitoring may take place in the post-closure period. Other post-closure requirements may include passive measures such as record keeping, and active measures such as restricting access to a site. A key consideration in planning such measures is that they should not jeopardise the isolation of the waste and the containment of radionuclides. The planned duration of active measures, including monitoring, varies between programmes, as does the period during which either active or passive measures can be relied upon in a safety case, in particular to deter human intrusion. A cautious approach is generally applied in which no credit is taken for such measures in averting or reducing the likelihood of human intrusion beyond around a few hundred years. This is because of the potential for societal changes and our inability to predict the priorities of future generations. The target time frame for active measures may be longer than this, however, for example to improve societal acceptance and confidence. Furthermore, measures that are more passive, such as durable markers or record keeping, may in reality inform future generations about the existence and nature of a repository over periods well in excess of a few hundred years.

Developing and presenting safety cases

In the interests of gaining, sharing and showing understanding of a system as it evolves over long timescales, it is useful to both define and develop means to address various time frames in a scientific and logical manner.

How to deal with generally increasing uncertainties in repository evolution and performance is a key problem to be addressed in developing a safety case. Quantitative safety assessment modelling tends to focus on potential radionuclide releases from a repository to the biosphere. The uncertainties affecting these models can generally be quantified or bounded and dealt with in safety assessment using, for example, conservatism or evaluating multiple cases spanning the ranges of uncertainty.

Where the consequence of calculated releases are expressed in terms of dose or risk, the biosphere must also be modelled. The biosphere is affected by human activities and relatively fast or unpredictable surface processes, and there is consensus that it is appropriate to carry out biosphere modelling on the basis of "stylised biospheres". That is, representations of the biosphere can be based on assumptions that are acknowledged to be simplified and not necessarily realistic, but are agreed and accepted internationally as valid for modelling studies.

Where regulations do not explicitly specify the time frames over which protection needs to be considered, the implementer has the challenge of deciding on the level and style of assessment to be carried over different time frames, which will then be subject to review by the regulator. Calculations of releases cannot, however, extend indefinitely into the future. Factors to be considered when deciding the time at which to terminate calculations of radionuclide releases include:

- uncertainties in system evolution which generally increase with time;
- the declining radiological toxicity of the waste – as noted above, spent fuel and some other long-lived wastes remain hazardous for extremely long times;
- the time of occurrence of peak calculated doses or risk;
- the need for adequate coverage of very slow long-term processes and infrequent events; and
- the need to address the concerns of stakeholders.

Truncating calculations too early may run the risk of losing information that could, for example, guide possible improvements to the system. Importantly, if the assumptions underlying the models are questionable in a given time frame, then qualifying statements must be made when presenting the results, so that they may be properly interpreted. The time frames covered by modelling in recent safety assessments range from 10 000 years to one hundred million years, although a million years seems to be emerging as a commonly accepted time frame in recent safety assessments.

In considering safety beyond the time frame covered by calculations of release, some programmes have developed arguments based on comparing the radiological toxicity of waste on ingestion with that of natural phenomena (e.g. uranium ore bodies; although the limitations of such arguments are acknowledged). Other lines of argument refer to the geological stability of a well-chosen site, which can provide evidence, for example, that uplift and erosion will not lead to exposure of the waste at the surface over timescales of millions of years or more. In practice, a number of different arguments may be presented, and different arguments may provide the most confidence in safety over different timescales, and to different audiences.

In the interests of communicating effectively with stakeholders and to build stakeholder confidence, safety cases need to be presented in a manner that communicates clearly how safety is provided in different time frames. This includes early time frames when substantially complete containment of radionuclides is expected, as well as later times, where some limited releases may occur. Non-specialist audiences are often (though not universally) most concerned about safety at early times – a time frame of the order of a few hundred years after emplacement. Especially when presenting safety cases to such audiences, it can be useful to emphasise the strong arguments for safety in this time frame. It may also be useful to devote a specific section of a safety report to explain the handling of different time frames, how uncertainties are treated (and how this varies with time), how multiple safety and performance indicators are used, and how to interpret the results as a function of time.

Refinement of understanding of key issues related to timescales coming from this work

The present document has revisited the various issues discussed in the earlier "lessons learnt" report of 2004, and discussed additional areas such as the planning of pre- and post-closure actions. For some issues, current understanding is unchanged compared to the 2004 document, whereas for others, some differences can be identified.

The timescales over which the safety case needs to be made

The 2004 document argued that ethical considerations imply that the safety implications of a repository need to be assessed for as long as the waste presents a hazard. The present report recognises that there are different and sometimes competing ethical principles that need to be balanced. It seems that the discussion of how to come to a balanced and socially acceptable view is still at an early stage in many nations and internationally. In addition, this discussion should be informed by inputs from a wide range of stakeholders, which is beyond the remit of the working group that produced this report.

The limits to the predictability of the repository and its environment

Both the 2004 document and the present report reflect a view that the limits to the predictability of the repository and its environment need to be acknowledged in safety cases.

Arguments for safety in different time frames

Both the 2004 document and the present report note that the types of argument and indicators of performance and safety used or emphasised may vary between time frames. The present report cites ongoing developments in the approaches to partition future time into discrete time periods and developments in phenomenological and functional analysis in different time frames.

The 2004 document observes that regulations are increasingly providing guidance on the use of lines of argument that are complementary to dose and risk. This observation is confirmed in the present report in the discussions of recent regulations and draft regulations in Sweden and the US. The present document emphasises that complementary lines of argument are required, not only to compensate for increasing uncertainties affecting calculated releases at distant times, but also to address other aspects of safety, especially continuing isolation, even at times beyond when quantitative safety assessments can be supported. Complementary arguments might be based, for example, on the absence of resources that could attract inadvertent human intrusion and on the geological stability of the site, with low rates of uplift and erosion. The argumentation for safety in the very long term is, however, an issue of ongoing discussion that is likely to require a consideration of ethical principles, since it relates to our ability and responsibility to protect the environment in the very remote future.

Interpretation of dose and risk calculated in long-term safety assessments

Both documents note international consensus that doses and risks evaluated in safety assessments are to be interpreted as illustrations of potential impact to stylised, hypothetical individuals based on agreed sets of assumptions. The assumptions are site-specific. Their basis, derivation, and level of conservatism can vary significantly; for this reason, the calculated results from safety cases should be carefully analysed if they are compared among national programmes.

Complementary safety and performance indicators

The 2004 document states that 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. Recent regulatory guidance cited in the present report shows that safety indicators and requirements are not only quantitative, but can include more qualitative concepts such as best available technique (BAT) and optimisation. This issue of how to evaluate compliance with requirements expressed in terms of qualitative indicators may, however, require further consideration, as may the interpretation of optimisation of protection when dealing with impacts across different timescales.

Addressing public concerns

Both documents note that the period of a few hundred years following emplacement of the waste may deserve particular attention in documents aimed at the public. The present document makes a number of other specific recommendations regarding the communication of how safety is provided in different time frames

Conclusion

In conclusion, the range of timescales that needs to be addressed within our safety cases presents considerable challenges. The decreasing demands on system performance as a result of the decreasing hazard associated with the waste with time partly offset the demands that increasing uncertainty (and decreasing predictability) place on safety assessment. Nevertheless, as discussed throughout this report, while some hazard may remain for extremely long times, increasing uncertainties mean that there are practical limitations as to how long anything meaningful can be said about the protection provided by any system against these hazards. Thus, time and level of protection – and assurance of safety – are linked to one another. These practical limitations need to be acknowledged in safety cases.

The various methods and approaches discussed in this report demonstrate that there are a range of approaches available now that can be called upon for developing and presenting safety cases. Furthermore, there is room to develop these approaches, for example, taking account of experience gained from stakeholder interactions to develop presentations suited to the needs of less technical audiences.

A general observation from the timescales questionnaire responses is that, in many programmes, a significant part of the final responsibility for the handling of timescales issues in safety cases is assigned to the implementer. Apart from setting safety criteria (that may or may not vary over time), the regulator's task is generally to review and point out any difficulties in the approaches to the handling of timescales issues adopted by the implementer. Wherever the final responsibility lies, a dialogue between the implementer, regulator and other stakeholders is valuable in resolving the issues in a manner that is widely accepted and such dialogue is ongoing in many programmes.

1. INTRODUCTION

1.1 Background to the present report

Geological repositories are sited and designed to isolate the waste from the environment normally accessible to humans and to contain its radioactivity and any chemically toxic components. Placing the waste deep underground in a suitable location ensures that the waste is not only inaccessible to humans, but also protected from surface events and processes. Containment by suitably chosen engineered and geological barriers means that releases from the repository are either prevented or, since some eventual releases can probably never be excluded, do not give rise to concentrations in the surface environment that would cause harm, at least over times that are of concern to regulators and other stakeholders.

The development of geological repositories is a step-wise process, proceeding in stages punctuated by decision points. At major decision points, an adequate safety case is often a prerequisite for a positive decision to move forward from one stage to the next (NEA, 2004b). Detailed scientific understanding and safety assessment methodologies have been developed in many programmes to provide the evidence, arguments and analyses to underpin safety cases for a range of repository concepts and geological settings. Definitions of the terms "safety case" and "safety assessment" are given in Box 1.1.

Box 1.1: **Definitions of a safety case and of safety assessment**

Both the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) and the International Atomic Energy Agency (IAEA) define a safety case as (NEA 2004b, IAEA & NEA 2006):

"... an integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the geological disposal facility."

The safety case draws not only on the results of quantitative modelling, but also more directly on site selection and the results of site characterisation and design studies, and also on the research programme and management strategy by which uncertainties and open questions are to be handled.

Safety assessment on the other hand is:

"... the process of systematically analysing the hazards associated with the facility and the ability of the site and design to provide the safety functions and meet technical requirements."

Challenges, however, remain. At the highest level the main challenge is associated with the long periods of time over which the radioactive wastes that are disposed of in repositories represent potential hazards, and the correspondingly long periods addressed by safety cases. Over such periods, repositories and their environments will be affected by events and processes characterised by many different time dependencies, and so a wide range of timescales and attending uncertainties have to be taken into consideration. A further challenge is how to show and document an understanding of how isolation and containment are sustained at all times considered. This is fundamental to any safety case, even though the focus of calculations is often on releases, which may only occur in the distant future.

The handling of issues related to timescales was discussed at an OECD/NEA workshop held in Paris on 16-18 April 2002. The workshop showed that issues related to timescales are of concern to all national programmes in the development of regulations and safety assessment methodologies and in building and presenting safety cases. The workshop also highlighted a trend in safety assessments and in safety cases to divide the post-closure period into either consecutive or overlapping "time frames", distinguished from each other by the presence or operation of different types of phenomena or uncertainties, or by the fact that different types of safety indicators or arguments are judged to be most suitable in each time frame. Definitions of the terms "timescales" and "time frames" are given in Box 1.2.

Box 1.2: **Definitions of timescales and time frames**

The terms "time frame", "timescale" and simply "time", as used extensively in this report, are, to some extent interchangeable. Generally, however, a "time frame" is taken to be a discrete time interval within the overall period addressed by a safety assessment or safety case. A time frame has a beginning and end. The term "timescale" is, on the other hand, used for a time interval the beginning or end of which are unspecified and may be arbitrary. For example, in the statement "climatic events and processes cause changes on a timescale of tens of thousands of years or more", the time at which change is taken to begin is not specified.

The Integration Group for the Safety Case (IGSC) decided at its 4th meeting, also in 2002, to create an ad hoc group to further explore issues raised at the timescales workshop – the Timescales Working Group[2]. The group produced a report (NEA, 2004a) providing a concise account of the lessons learnt and issues raised at the workshop with the aim to be accessible to a wider audience compared to the detailed workshop synthesis (NEA, 2002). Key subjects addressed in this report on lessons learnt concern:

- the timescales over which the safety case needs to be made;
- the limits to the predictability of the repository and its environment;
- arguments for safety in different time frames;
- stylised approaches;
- complementary safety and performance indicators; and
- addressing public concerns.

There is, however, an evolving understanding regarding the nature of the issues related to timescales and how they should be addressed. Thus, a further programme of work for the Timescales Working Group, as outlined below, was agreed at the 5th IGSC meeting, leading to the production of the present report.

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[2] Peter de Preter of ONDRAF/NIRAS (see the acronym list – Appendix 2 – for key to abbreviations) heads the group. Other members are Lise Griffault and Sylvie Voinis (Andra), Philippe Raimbault (DGSNR), Jesus Alonso (Enresa), Thomas Beuth and Klaus-Jürgen Röhlig (GRS), Johannes Vigfusson (HSK), Jürg Schneider (Nagra), Hiroyuki Umeki (NUMO, now JAEA), Risto Paltemaa (STUK), Lucy Bailey (Nirex), David Sevougian and Abe Van Luik (US-DOE-YM), Claudio Pescatore (NEA) and Paul Smith (SAM Ltd., consultant).

1.2 Aims, added value and intended audience

The aims of the present report are:

- to review the current status and ongoing discussions on the handling of issues related to timescales in the deep geological disposal of long-lived radioactive waste,
- to highlight areas of consensus and points of difference between national programmes; and
- to determine if there is room for further improvement in methodologies to handle these issues in safety assessment and in building and presenting safety cases.

Compared to the synthesis of the 2002 workshop and the "lessons learnt" report, the present report draws on the experience of more participating organisations. Implementing organisations, regulators and scientific and technical institutes and advisory bodies from thirteen OECD member countries contributed via their responses to a questionnaire and via their participation in subsequent meetings (see below). The report also takes account of progress in the handling of timescales issues in safety cases since 2002, and includes more specific examples than the earlier documents.

The report is aimed at interested parties that already have some detailed background knowledge of safety assessment methodologies and safety cases, including safety assessment practitioners and regulators, project managers and scientific specialists in relevant disciplines.

1.3 Mode of operation

The following programme of work was carried out between March 2004 and December 2005:

- the Timescales Working Group prepared a questionnaire to provide background information for the present document;
- a first version of the questionnaire was tested on a small group of implementing organisations and regulatory bodies and modified according to their feedback;
- the final questionnaire (Appendix 1) was distributed to relevant organisations represented within IGSC; twenty-four organisations, including implementers, regulators and scientific and technical institutes and advisory bodies from thirteen NEA countries, responded to the questionnaire,
- the main points and issues identified from the responses were collated and discussed at a seminar meeting held on 10-11 May 2005; the structure and contents of a state-of-the-art report were also discussed;
- the present report was drafted, based on the above steps plus discussions that took place at a meeting held in La Coruña, Spain on 23 August 2005; presentations and discussions at a topical session at the 7th meeting of the IGSC held in Paris on 13 October 2005; and a final meeting, also held in Paris, on 7-8 December 2005.

This procedure allowed some developments to be considered in this report, even though they occurred later than the questionnaire response deadline, an example being the US Environmental Protection Agency (US EPA) and Nuclear Regulatory Commission (US NRC) draft standard and regulation for Yucca Mountain (US EPA, 2005, US NRC; 2005) being out for public comment and review.

1.4 Report structure

The handling of issues related to timescales is affected by a number of general considerations, which are described in Chapter 2. These include:

- ethical principles;
- the evolution of the hazard associated with the waste;
- the evolution of repository systems and associated uncertainties; and
- the stability and predictability of the geological environment.

The succeeding chapters of the report then discuss three broad areas in the regulation and practice of repository planning and implementation affected by timescales issues:

- Chapter 3: repository siting and design and the levels of protection required in regulation;
- Chapter 4: the planning of pre- and post-closure actions; and
- Chapter 5: developing and presenting a safety case.

In each of these chapters, the current status, ongoing discussions and points of consensus and divergence identified among the national organisations taking part in the discussions are described as appropriate.

Finally, in Chapter 6, conclusions are drawn, including a re-evaluation of the statements made in the 2004 "lessons learnt" report.

A list of acronyms used in the report is given in Appendix 2. The organisations that provided material for this report by responding to the questionnaire, their roles within their respective national programmes, the status of these national programmes, and the particular disposal systems to which the responses related are described in Appendix 3. A question-by-question summary of the main points and issues identified from the questionnaire responses is given in Appendix 4.

2. GENERAL CONSIDERATIONS IN THE HANDLING OF ISSUES OF TIMESCALES

2.1 Ethical principles

2.1.1 Ethical considerations in waste management

Decision making in radioactive waste management needs to take account of the responsibilities and obligations of the present generation to others. There are thus ethical issues to be considered concerning, for example, our duty to future generations in terms of the levels of protection that should be provided.

Key ethical principles relevant to waste management in general, and geological disposal in particular, are introduced in the following sections, and the difficulties in meeting them in practice (i.e. translating them into performance objectives) are discussed.[3] It is not, however, intended to give a comprehensive and detailed discussion of all ethical and philosophical considerations that may have a bearing on these issues. The discussion shows that relevant ethical principles are open to different interpretations and can sometimes compete. The interpretations made and balance struck between competing principles is a matter of judgement and may vary between different countries and stakeholder groups, and remain matters of discussion internationally. The distinction between fundamental ethical principles and objectives, and secondary principles or considerations that are identified in order to meet or satisfy these higher-level principles and objectives, is also currently a matter of some discussion. The Long-term Safety Criteria (LTSC) Task group of the NEA Radioactive Waste Management Committee (RWMC) is currently working to advance the state of the art in these areas.

2.1.2 Long-term protection

Given the long timescales over which radioactive waste presents a hazard (Section 2.2), decisions taken by humans now and in the near future regarding the management of the waste can have implications for the risks to which generations in the far future may be exposed. Considerations of fairness and equity between the present and future generations are embodied in the principle of intergenerational equity, the application of which has evolved to encompass three aspects:

1. Protecting future generations from harm.
2. Avoiding imposing undue burdens on those future generations not benefiting from the activities that created the hazard.
3. Maintaining flexibility or a range of choices open to future generations in their decision making.

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[3] The basis of the discussion is the outcome of meetings held subsequent to the compilation of responses to the questionnaire. The questionnaire itself did not address ethical principles.

In 1995, the NEA published a Collective Opinion on the environmental and ethical basis of the geological disposal of long-lived radioactive waste (NEA, 1995). According to this Collective Opinion, geological disposal:

> *"takes intergenerational equity issues into account, notably by applying the same standards of risk in the far future as it does to the present, and by limiting the liabilities bequeathed to future generations ..."*

It also states that, as a guide to making ethical choices in waste management, the waste should be managed in a way that:

> *"... affords to future generations at least the level of safety which is acceptable today; there seems to be no ethical basis for discounting future health and environmental damage risks..*

Similar objectives are set out in the IAEA Safety Fundamentals (IAEA, 1995):

> *"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.";*
>
> and
>
> *"Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations."*

While there is consensus that the current generation has a responsibility not to compromise the interests of future generations, there is some divergence of views as to how far into the future (to how many generations) this responsibility extends. In many applications, the principle of intergenerational equity is considered to apply only over a few generations.[4] All concepts for geological repositories that are currently under consideration are expected to protect human beings and the environment well beyond a time frame of a few generations, and thus, meet the objective of protecting future generations at least as well as other industrial waste applications do. In fact, the radioactive waste community typically considers that this objective applies over far longer timescales, and sometimes even indefinitely into the future. NEA (2004a), for example, states:

> *"... 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."*

These technical difficulties are essentially the uncertainties associated with making assessments of system safety over long timescales (Section 2.3).

Some uncertainties may be reduced or their impact mitigated by siting and design measures. Such measures, however, generally involve the utilisation of resources and the cost of doing so must be balanced against the corresponding benefit in terms of uncertainty (or risk) reduction when evaluating the acceptability of a waste disposal option. Thus, in "constrained optimisation", which is the main approach to evaluating the acceptability of a waste disposal option advocated by the International Commission on Radiological Protection (ICRP 2000):

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[4] Disposal techniques in shallow landfills for chemically toxic wastes and environmental assessments for these facilities typically address periods of tens or occasionally hundreds of years – even though the disposed substances may, in some cases, remain toxic indefinitely. Longer timescales are, however, also sometimes considered for such wastes, for example when they are disposed of in underground caverns.

> *"... optimisation of protection is a judgmental process with social and economic factors being taken into account ... The goal is to ensure that reasonable measures have been taken to reduce future doses to the extent that required resources are in line with these reductions."*

In the United States, the National Academy of Public Administration (NAPA) has proposed four basic objectives or principles (NAPA, 1997):

- **Trustee**: Every generation has obligations as trustee to protect the interests of future generations.
- **Sustainability**: No generation should deprive future generations of the opportunity for a quality of life comparable to its own.
- **Chain of obligation**: Each generation's primary obligation is to provide for the needs of the living and succeeding generations. Near-term concrete hazards have priority over long-term hazards.
- **Precautionary**: Actions that pose a realistic threat of irreversible harm or catastrophic consequences should not be pursued unless there is some countervailing need to benefit either current or future generations[5].

The need for responsible use of resources by the present generation follows from both the trustee and the sustainability principles. There is also a widely held pragmatic recognition that the same depth and types of argument used to show a given level of protection may not be achievable or available irrespective of time, as a result of uncertainties in the performance of geological repositories, which generally increase with time. Some argue that in view of these difficulties the capacity of the present generation to assume responsibility for the protection of future generations changes with time (KASAM, 2004). This has led, for example, to the statement by the US EPA in its draft rule for Yucca Mountain, that a repository (US EPA 2005, p. 96):

> *"must provide reasonable protection and security for the very far future, but this may not necessarily be at levels deemed protective (and controllable) for the current or succeeding generations."*

An emphasis on nearer-term concrete risks over longer-term more hypothetical risks is also a part of the chain of obligation principle (above).

This view is not, however, universally shared. In particular, others argue that, in spite of the difficulties presented by increasing uncertainties, the responsibilities of the present generation to future generations remain unchanged over time.

Thus, a consideration of ethical objectives does not give unequivocal guidance when it comes to the details of long-term protection. The US EPA remarks that (US EPA, 2005, pp 78-79):

> *"we struggled to reconcile the competing claims of confidence in projections and intergenerational equity."*

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[5] There are different versions of the precautionary principle or approach. However, Principle 15 of the United Nations Conference on Environment and Development (the Rio Declaration) provided a statement of the approach that has been agreed at an international level: "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (UN, 1992).

Different and sometimes competing objectives may need to be balanced, along with pragmatic considerations of what is possible in practice. The weighting assigned to particular objectives is often a matter of societal judgement and can thus vary between national programmes. This is reflected in the fact that regulations differ between nations in terms of whether requirements for long-term protection vary as a function of time, as discussed in Section 3.3. In the end, it is unclear if and how a technical safety case can include and address these issues. This exercise simply shows that they cannot be forgotten, and that they need to be considered in a broader context than the technical safety case alone.

2.1.3 Phased planning and implementation of repositories

Decisions regarding the planning and implementation of repositories, and particularly whether to close a repository at the earliest practical time or to plan for an extended open period, also have an ethical dimension. The planning and implementation of geological repositories is often divided into discrete and to some extent reversible phases, the objective being to provide both the present and future generations with a range of options regarding the rate at which they proceed towards closure, and the possibility to revise the disposal strategy if they so wish. The ethical basis for this approach is provided by considerations of fairness and equity not only between present and future generations, but also within contemporary generations (intra-generational equity), which lead to a requirement for a fair, open and inclusive decision-making process when planning and implementing a geological repository, including the decision regarding final closure. The NEA Collective Opinion of 1995 (NEA, 1995) stated that geological disposal:

> *"takes intragenerational equity issues into account, notably by proposing implementation through an incremental process over several decades, considering the results of scientific progress; this process will allow public consultation with interested parties, including the public, at all stages."*

The Collective Opinion also states that:

> *"retrievability is an important ethical consideration since deep geological disposal should not necessarily be looked at as a totally irreversible process, completely foreclosing possible future changes in policy."*

The Roundtable on Ethics conducted by the Nuclear Waste Management Organisation (NWMO) in Canada (Appendix 7 in NWMO, 2005) identified as ethical questions meriting special consideration:

> "*Are sound provisions being made to check on whether management provisions are working as designed? If problems appear, are provisions being made to gain the access needed to fix them? Is the issue of reversal if something goes seriously wrong being taken into account?*"

> "*Is it ethically acceptable to seek a permanent solution now or would it be preferable to recommend an interim solution in the hope that future technological improvements might significantly lower the risks or diminish the seriousness of the possible harms?*"

Such considerations have led to concepts in which backfilling of access routes and final closure of the repository are deferred to provide a period during which the waste can readily be monitored and retrieved if required (Chapter 4).

A repository that is left open requires active measures to be taken to provide protection of humans and the environment and security of the disposed materials. If the open period is to extend for up to several hundred years, which is an option, for example, in the UK Phased Geological Repository

Concept (PGRC) for intermediate-level waste and certain long-lived low-level waste (Nirex, 2005), then these measures will have to be undertaken by future generations, who will also be required to take the decision as to if and when to close the repository. Considerations of intergenerational equity thus also become relevant here.

Phased disposal concepts provide for intergenerational equity in as far as they allow next generations flexibility in their own decision making, giving them the freedom of choice, if they so wish, to retrieve the waste as a resource or to revise the disposal strategy. They can, however, also be seen as conflicting with the objective of intergenerational equity in that they transfer a burden of responsibility for the safe management of wastes generated by the present generation to future generations. Thus, the Canadian Roundtable on Ethics also identified risk reduction vs. access as an ethical question meriting special consideration:

> "*What is the appropriate balance between reducing risk to the greatest extent possible and retaining access to the materials, for remediation, for example, or to recover valuable materials from them?*"

Thus again, ethical considerations do not provide unequivocal guidance – this time on issues of the phased implementation of repositories and, in particular, whether to close a repository at the earliest practical time, or to plan for an extended open period. Furthermore, adopting an extended open period also introduces uncertainties, which grow with time: in particular, regarding the continuity of institutions and the ability to ensure the necessary knowledge and resources are passed to future generations to properly manage the facility. So, its implementation and assessment also carry practical limitations. As before, a balance is required between different and sometimes competing objectives and it is a matter of social judgement how this balance is struck.

2.2 The hazard associated with radioactive waste

2.2.1 Nature of the hazard

Radioactive waste is a hazardous material requiring safe long-term management. This is because of (i), the potential dose due to external irradiation which would be received (principally from gamma rays and to a lesser extent neutrons), for example, by humans in close proximity to waste and in the absence of isolation or adequate shielding, (ii), the potential dose due to the ingestion or inhalation of radionuclides if, for example, radionuclides in the waste were to be released to the environment, and (iii), the potential effects of the presence of chemically toxic materials in the waste itself or its packaging (which may make the highest contribution to toxicity in the case of some low-level wastes disposed of deep underground).

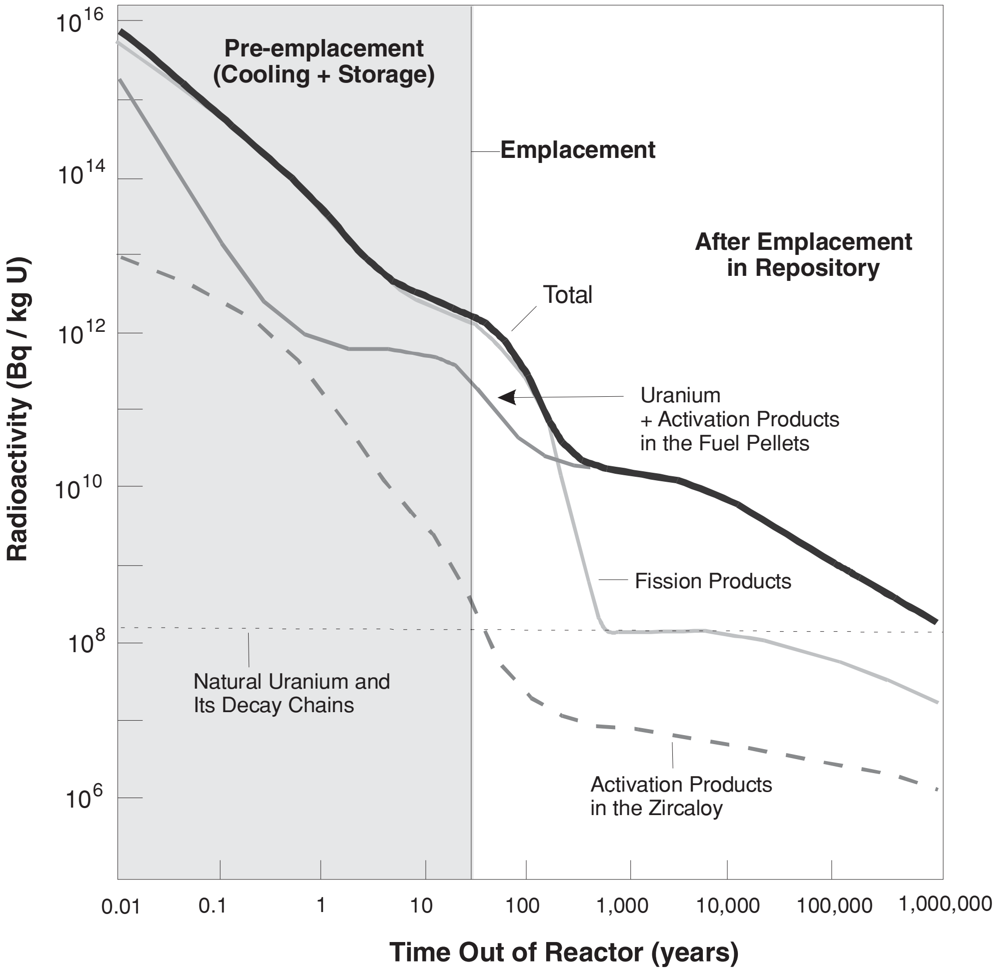
2.2.2 Evolution of the hazard

The radioactivity of waste disposed of in a geological repository will decay significantly over time, as illustrated in Figure 2.1 in the case of Canadian spent fuel (SF). This decrease in radioactivity and its associated hazards is in marked contrast to chemically toxic waste, since stable chemically toxic materials remain equally toxic indefinitely (although, as noted above, some stable chemically toxic materials may be present in radioactive waste and its packaging).

Radioactive decay increasingly reduces the potential doses due to external irradiation and to ingestion or inhalation of radionuclides if isolation and containment are compromised at some future time. Thus, the greatest demands on a geological disposal system in terms of the need for protection arise at early times when the level of radioactivity of the waste is at its highest. In the case of spent fuel and vitrified high-level waste (HLW), for example, this may provide motivation for an initial period (several hundred years or more) of substantially complete containment of the waste within specially designed containers.

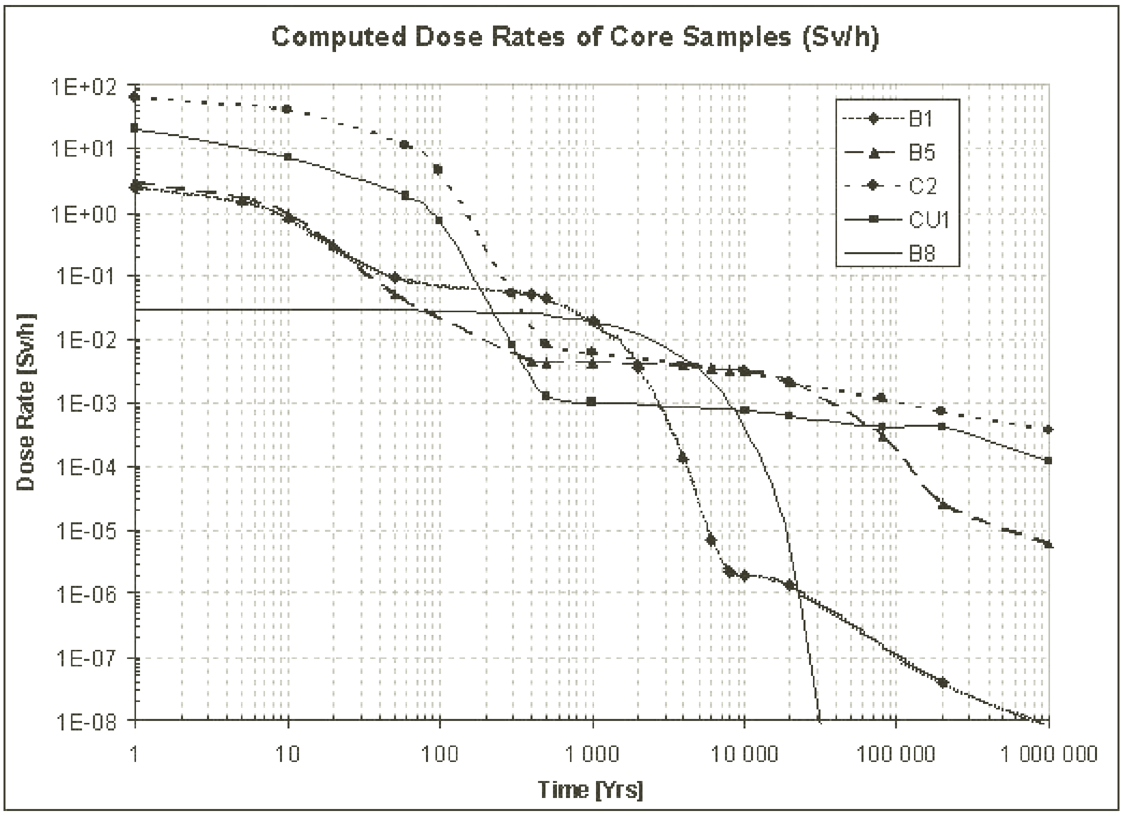
The half-lives of the isotopes in radioactive waste, however, vary widely. Although many decay substantially early in the evolution of a repository, others, such as ^{238}U with a half-life of 4.5×10^9 years, will persist for much longer (again, see Figure 2.1). Other radionuclides (especially some of those created artificially in nuclear reactors) that could be important in terms of the hazard from external radiation also persist out to one million years or longer, as shown by the calculations in Figure 2.2. Thus, even though the hazard potential of spent fuel and some long-lived wastes decreases markedly over time, these wastes can never be said to be intrinsically harmless.

Figure 2.1: **An example of the decrease of the activity of Canadian spent fuel over time due to radioactive decay (from the Atomic Energy of Canada Limited 1994 Environmental Impact Statement, AECL, 1994)**



Note: Natural uranium refers to pure (100%) uranium with the relative amounts of different uranium isotopes being those found in uranium ore

Figure 2.2: **Calculated dose to workers in a hypothetical scenario in which a borehole is drilled through spent fuel and high-level waste packages and core extraction gives rise to external radiation exposure from the French Dossier 2005 Argile. Each line corresponds to a single waste package of a given type being affected (see Andra, 2005a-c for an explanation of the waste types). A human intrusion scenario is used to assess potential doses from external exposures, but the results can be viewed as representing the intrinsic hazard since similar trends would be expected from external exposures through other scenarios in the absence of isolation or adequate shielding**[6]



2.3 Repository evolution and its associated uncertainty

Repository sites and engineered barrier designs are chosen with long-term stability and predictability as important considerations. They are not, however, static systems. The excavation of underground openings and the emplacement of engineered materials, including the wastes themselves, create thermal, hydrogeological, mechanical, chemical and biological perturbations, and it can take up to a few thousand years for the repository and its geological environment[7] to evolve to a new state of "quasi-equilibrium". The repository may also be subject to external changes, due, for example, to climatic events and processes over timescales of tens of thousands of years or more. Geological events and processes can also lead to changes over sufficiently long timescales. Box 2.1 describes in more detail general factors affecting how a repository and its geological environment change over time.

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6. At one million years, the external dose rate is due predominantly to daughters of ^{237}Np, of which ^{209}Tl requires the most shielding.

7. The geological environment of a repository, or geosphere, is generally taken to be the undisturbed host rock (the rock in which the waste is emplaced) plus any underlying or overlying geological formations that contain potential paths or act as barriers for radionuclide transport to the biosphere.

Repository evolution is inevitably subject to uncertainties. With the possible exception of the evolution of overall radioactive inventory,[8] precise "predictions" are not possible over long timescales. Uncertainties can to some extent be avoided or their impact mitigated through appropriate siting and design decisions, and can be reduced in the course of a comprehensive site characterisation and research programme. They can, however, never be completely eliminated.

Box 2.1: **General factors that affect how a repository and its geological environment change over time**

Changes are, to a large extent, site and design specific. In general terms, however, they are the result of the following broad categories of events and processes:

Early transient processes

Thermal,[*] chemical, hydraulic, mechanical gradients and radiological and biological processes resulting from the construction of the repository, emplacement of the wastes and any pre-closure open phase and closure of the repository give rise to transient mass and energy fluxes that decrease over timescales of, typically, hundreds to thousands of years. As discussed in Chapter 4, the degree to which the pre-closure phase influences post-closure evolution is concept specific.

Internal interactions

Interactions between the different engineered components of the repository (including the waste itself), and between the engineered components and the geological environment may occur over a wide range of timescales. Included are slow processes such as the corrosion of waste containers on contact with water vapour or liquid water entering the repository, and the migration into the host rock (and interaction with it) of high-pH leachates from cementitious repository materials.

Endogenic and exogenic perturbations

Endogenic perturbations are those resulting from underground geological phenomena. The geological settings of repositories are generally chosen for their physical and chemical stability and capacity for providing a long-term protective environment for the repository and its waste. Long-term changes may, however, take place as a response to slow processes such as uplift or subsidence, and infrequent events, including, for example, earthquakes of tectonic origin.

Exogenic perturbations are those resulting from phenomena external to the surface of the Earth, such as climate change and possible detrimental future human actions such as drilling in the vicinity of the repository. The earth's overall climate is expected to stay warm for another 10 000 to 20 000 years, but significant changes may occur after this time.

* Especially relevant for the cases of spent fuel and vitrified high-level waste.

Most uncertainties increase the further into the future that assessments are made. This is not, however, always the case, and some features or processes may become less uncertain in longer time frames. For example, processes driven by temperature gradients within and around a repository may be subject to significant uncertainty for as long as the waste generates significant heat. In the longer term, however, once the "thermal phase" has passed, the temperature gradients diminish and these processes are confidently expected to cease. The same applies to any other transient process in which

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[8] Even here, the half-lives of all relevant radionuclides are not known with complete "certainty". For example, the half-lives of ^{79}Se and ^{126}Sn have been revised within the last decade.

gradients diminish over time and are finally balanced. The tendency, however, is for increasing uncertainty with longer-term prognoses. Taking again the example of temperature, in the still longer term (beyond the thermal phase) the possibility of geothermal phenomena may need to be considered, which will again introduce a whole suite of uncertainties regarding likelihood, timing, magnitude, and potential effects.

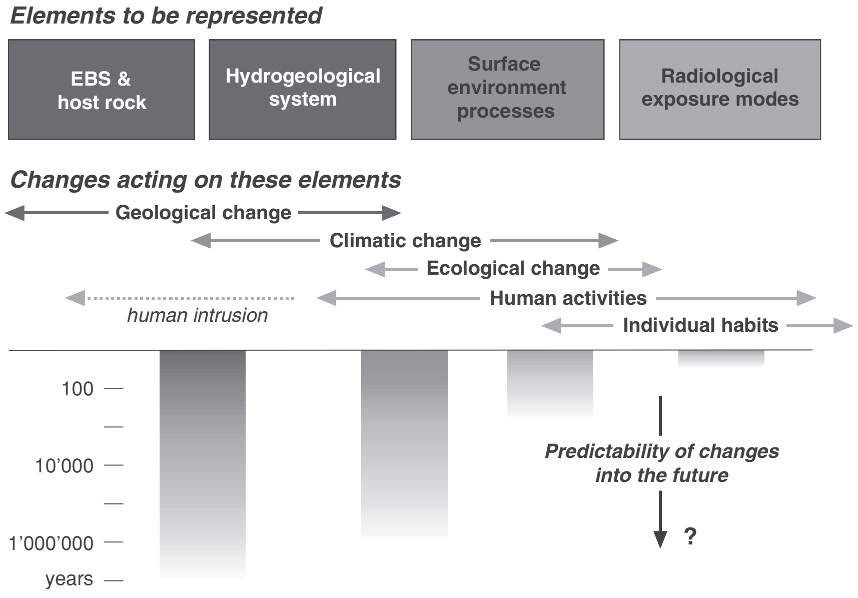
The tendency of uncertainties to increase is partly because scientific understanding of slow processes and infrequent events is often based on a more limited amount of empirical information than is available for more rapid processes and frequent events. Also, some events and processes may be so slow or infrequent that they (and their associated uncertainties) are irrelevant over short time frames, but need to be taken into account in the longer-term. Uplift and erosion, for example, may be irrelevant over a thousand-year time frame, say, but may need to be taken into account in assessments over a time frame of a million years.

The isolation of waste far underground lessens the risks (and the uncertainties) from perturbing events related to human habits and intrusive actions in the near term (hundreds of years, for example) – as well as short-term climate cycles – that may be important, for example, in assessing risks for surface storage. For a well-sited and well-designed repository, any loss of isolation (e.g. by uplift and erosion) is likely to occur only in the distant future. Furthermore, any releases of radionuclides from the underground facility are expected to reach the human environment only after a prolonged period of retention (or slow transport) in the repository itself and in the geosphere (the releases will be further attenuated by radioactive decay and by spreading of the releases in time). Thus, the strategy of isolating the waste and containing its radionuclides that underlies all geological disposal concepts leads, by its very nature, to the potential of exposure only in the distant future when uncertainties are large.

Figure 2.3 illustrates how increasing uncertainties limit the predictability of changes that act on different system components. The figure shows the elements generally represented in safety assessment modelling, including the engineered barrier system and host rock, the hydrogeological system, surface environment processes and radiological exposure modes, and the various changes that act on these elements. It shows how the evolution of the engineered barrier system and host rock, which is affected by slow geological changes or potentially by low probability events such as human intrusion, tend to be predictable further into the future than the hydrogeological system, which is affected to some extent by more rapidly changing climatic and ecological conditions and by human activities. Surface environment processes are affected to a greater extent by these more rapid changes, as well as by changes in individual human habits, and are thus predictable over shorter timescales. Radiological exposure modes, which are closely related individual human habits, can be predicted with confidence only in the very short term (long before any exposures are likely to occur from a closed repository). The treatment of uncertainty in safety assessment is discussed in Chapter 5.

The decreasing demands on system performance as a result of the decreasing hazard associated with the waste with time partly offset the demands that increasing uncertainty (and decreasing predictability) place on safety assessment. Nevertheless, as discussed throughout this report, while some hazard may remain for extremely long times, increasing uncertainties mean that there are practical limitations as to how long anything meaningful can be said about the protection provided by any system against these hazards. Thus, time and level of protection – and assurance of safety – are linked to one another. These practical limitations need to be acknowledged in safety cases. Likewise, operational definitions of safety may need to acknowledge and make explicit the time component over which the definition (or level of protection) is assumed to be applicable or demonstrable.

Figure 2.3: **Elements generally represented in safety assessment modelling, the changes that act on these elements and the impact on the predictability of the elements over time (from NEA, 1999c).**



2.4 Stability and predictability of the geological environment

A suitable geological environment is a cornerstone of geological disposal. Although many geological environments are potentially suitable for disposal, a high priority in site selection in all repository programmes is that the site should both:

- ensure the safety of a suitably designed repository; and
- enable information to be obtained (preferably at early stages of a programme – the attribute of explorability) that allows performance to be assessed for a reasonable period of time, often up to a few million years into the future.

Thus, ideally, a site should be both geologically stable, which is a requirement for safety, and broadly predictable to the extent required to provide a basis for assessing performance.[9] Many national programmes have identified sites that are believed to be stable and broadly predictable over a time frame of a million years or more, while others plan to search for such sites (Appendix 4, observations from the responses to Question 4.2).

A stable geological environment is one that is not likely to be subject to sudden or rapid detrimental changes over long timescales due to its buffering capacity with respect to internal and external perturbations. In assessing geological stability, it is thus necessary to identify and characterise both slow, continuous processes such as uplift and erosion, and infrequent events, such as major earthquakes and volcanism. In the context of geological disposal, a site is generally considered to be

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[9] The stability and the predictability of the geological environment (or any system component) are clearly related. Nevertheless, the period during which well-supported statements about the evolution of a component can be made does not necessarily coincide with the period during which the component will, in reality, remain stable.

geologically stable if perturbing geological events and processes can either be excluded, or shown to be sufficiently rare, slow, or the consequences sufficiently small that repository safety will not be compromised over the required time frame.

The time frame over which the broad characteristics of a stable geological setting can be predicted or assessed is large but, as with all system components, is limited by the presence of uncertainties (see, for example, Figure 2.3). The predictability of a particular setting depends on the degree to which its geological history is understood, and on how far into the future an understanding of geological history is deemed to allow projections to be made. Understanding of the geological history of a site can in some cases indicate a history of stability of tens to hundreds of millions of years, which lends support to an assumption of continued geological stability in the future (e.g. Mazurek *et al.,* 2004).

It should finally be noted that a stable geological setting with favourable rock properties, although important, is only one of several factors that influence site selection, and has to be balanced against other safety considerations. For example, factors could include the presence of any natural resources that might give rise to inadvertent human intrusion when records of the repository have been lost. Others may relate to operational safety and engineering feasibility, rather than to long-term safety, including, for example, the need to develop a reliable transport infrastructure to support repository construction and operation.

3. REPOSITORY SITING AND DESIGN AND THE LEVELS OF PROTECTION REQUIRED IN REGULATION

3.1 Providing long-term isolation and containment

3.1.1 Robustness

The safety of geological repositories, and in particular the possibility to show that adequate levels of isolation and containment are provided over the timeframes addressed by safety cases, requires that these systems are robust with respect to the perturbing phenomena and uncertainties that may arise over these time frames. Thus, as far as reasonably possible, events and processes that could be detrimental to isolation and containment, as well as sources of uncertainty that would hamper the evaluation of how the systems evolve over time, are avoided or reduced in magnitude, likelihood or impact.

There are both common features and differences in the ways in which different disposal systems achieve robustness in different time frames. Common features are the need for *passive safety* throughout the post-closure period provided by *multiple safety functions or barriers*, and the importance of *stable and predictable* system components or barriers, including the geological environment – Section 2.4, in contributing to these safety functions over long timescales. There are also, however, some differences in the nature of the safety functions provided by different systems and the way in which their contribution to safety and the safety case evolves over time.

3.1.2 Passive safety

The term "safety", in the context of radioactive waste disposal, may be defined as follows [NEA/RWM(2006)13]:

> *"Safety, as understood technically, is an intrinsic property of the disposal system as implemented, i.e. the absence of physical harm resulting from the existence and operation of the system over a given period of time. Harm is unacceptable impact, and varies with context. The term "system" represents all the arrangements that make it work, including technical and administrative measures (such as institutional controls)."*

There is consensus that geological repositories should provide for protection throughout the post-closure period by passive means. Passive safety means that isolation and containment do not require the typical human actions that provide, for example, supervising and controlling structures, financial resources and human specialist knowledge (e.g. HSK & KSA, 1993). A passively safe repository, therefore, allows a safety case to be made that does not rely on the presence of man for its proper functioning.

The aim of good system design and good engineering for any type of disposal system (as well as other engineered systems where there is the potential to cause harm) is always to promote passive safety and "fail safe", and to minimise need for active controls. Depending on the system, active controls may also be needed during some time period or may provide additional assurance. In the case of geological repositories, however, post-closure safety must specifically be assured without invoking active measures. This is because a waste management system that depended for its safety on active controls would not only be vulnerable to any failure of supervising and controlling structures, but could also be seen as placing undue burdens on future generations, and thus be inconsistent with the principle of intergenerational equity (Section 2.1).

Passive safety does not necessarily mean that monitoring and controls are excluded. It is certainly planned that geological repositories will be monitored during the construction and operational period, and also to some extent after closure; any perturbations from expected behaviour are likely to be evaluated to understand their significance to post-closure safety. Monitoring and control may be considered to contribute to public acceptability and "defence in depth" in a safety case (Section 4.2). The disposal system must, however, be capable of providing a sufficient degree of safety without continuously relying on such measures [IAEA and NEA, 2006**,** NEA/RWM/IGSC(2005)3]. IAEA safeguards requirements are to be promulgated that suggest that a minimal programme for monitoring of the physical security of the repository may be necessary as long as a society exists that is capable of doing so, but this is not the type of monitoring that detects changes in the performance of the repository.

3.1.3 Multiple safety functions

The term "safety function" is defined in Box 3.1. At any time, the existence of multiple safety functions, provided via a range of physical and chemical phenomena with no undue reliance on any single barrier or phenomenon, is recognised by all programmes as contributing to robustness by mitigating the effects of uncertainties on the overall performance of a repository, and reducing the possibility that any single perturbing phenomenon or uncertainty can undermine all of the functions. There is value in expressing how a repository provides safety as a function of time in terms of the evolving safety functions that the system provides rather than in terms of barrier evolution, as illustrated by the examples given in Chapter 5.

Box 3.1: **Safety function – definition from DGSNR *et al.* (2004)**

A function can be defined as any action that a system or one of its components must carry out in order to achieve a given purpose. The functions of a disposal system contribute to fulfilling the different objectives assigned to it. Safety functions are those functions that make it possible to comply with the principles of safety and radiological protection as well as with the basic objective of protection during all stages of the life of the facility, while limiting the burden for future generations.

More than one system component can contribute to a single safety function. For example, where the prevention or limitation of access of water to the waste is defined as a safety function (e.g. Figure 5.5), this can be provided by a tight geosphere and/or the capacity of certain engineered barriers (including seals) to delay the ingress of water. Furthermore, a single system component can contribute to more than one safety function – for example, iron or steel canisters can provide a period of complete containment of radionuclides, and their corrosion products can also contribute to geochemical retention of released radionuclides subsequent to canister breaching. The avoidance of significant adverse effects of one system component on the safety functions provided by another is a general consideration in repository design (e.g. physical damage by gas pressure developed as a result of gas generation by the corrosion of steel components).

3.1.4 Stability of the system components or barriers and predictability of their evolution

Stable and predictable system components, and in particular a stable and predictable geological environment, are fundamental to all repository concepts (Sections 2.3 and 2.4). Geological stability and predictability over long timescales is a requirement, or is implied as being realistically attainable, in some national regulations and in the statements made by advisory bodies in some nations (Appendix 4, observations from responses to Question 3.1). It should be noted that the possibility of perturbing events such as earthquakes and volcanism does not necessarily preclude a site, although this depends on national criteria. For example, German proposals for siting criteria (AkEnd, 2002) include the following exclusion criteria applying to the repository area in terms of earthquake and volcanism:

- the expected seismic activity must not be higher than in Earthquake Zone 1 as defined in the German seismic regulation DIN 4149; and
- there must neither be any quaternary nor any expected future volcanism.

These German proposals require a site to be found where performance of the "isolating rock zone" can be demonstrated over at least a million years (based on this, draft German safety criteria require quantitative assessments only over this timeframe).[10]

In the United States, the National Academy of Sciences of the National Research Council suggested a period of regional geological stability "on the order of one million years" over which projections of the performance of a Yucca Mountain repository could credibly be made and compliance assessed (1995) Subsequently, regulations required performance assessments to calculate the peak dose that would occur "after 10 000 years following disposal but within the period of geologic stability" and to be published in the Environmental Impact Statement (US DOE, 2002a) but not to be subject to dose limits.[11] Recent proposed changes to these regulations would define the time period more specifically to end at one million years after disposal (and would also apply a dose limit to projected doses for time periods between 10 000 and 1 million years).[12] On the other hand, according to current Hungarian guidance, 10 000 years is the minimum period for which host rock stability must be demonstrated.

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[10] See B. Baltes and K-J. Röhlig (GRS) in EUROSAFE Forum 2005. Safety Improvements – Reasons, Strategies, Implementation. Brussels, 7-8 November 2005. See Web link: www.eurosafe-forum.org/products/data/5/pe_394_24_1_seminar5_01_2005.pdf

[11] The "period of geologic stability" was defined as the time during which the variability of geologic characteristics and their future behavior in and around the Yucca Mountain site can be bounded, that is, they can be projected within a reasonable range of possibilities.

[12] EPA has published a proposed rule (US EPA, 2005), for public comment, changes to current standards. These changes were made in response to a court decision vacating the 10 000 year compliance period on the basis that EPA had not provided adequate justification for not incorporating a compliance measure at the time of peak dose, as recommended by the National Academy of Sciences. As required by statute, NRC will modify its regulations consistent with any changes made by EPA, and has also published its proposed changes for public comment (US NRC, 2005).

3.2 Roles of the barriers and safety functions as functions of time

3.2.1 Changing emphasis over time

Some safety functions contribute to safety at all times considered, whereas others contribute over limited time frames (Appendix 4, observations from responses to Question 3.2). The isolation of the waste from humans is regarded as an essential function of the geological environment, and must be provided at all times considered in a safety case. Thus, the factors that are taken into account in site selection generally include low rates of uplift and erosion in the siting region, low likelihood of significant disturbances to a repository by geological phenomena such as seismicity and volcanism, and absence of resources that might attract disturbance by humans. On the other hand, both the geological environment and the engineered barriers can contribute to ensuring that radionuclides are substantially contained, and the roles of the different system components in this regard can vary as a function of time. For example, engineered barrier concepts for spent fuel and vitrified high-level waste are generally designed to provide an initial period of substantially complete containment over a time frame of at least several hundred years in order to mitigate the effects of uncertainties associated with transient, thermal and hydraulic processes. Thereafter, in many (though not all) safety cases, emphasis tends to shift with time to delay and attenuation of releases by the engineered barriers and finally to delay and attenuation of releases provided by the geological barrier. Most programmes aim for containment of the major part of the radionuclide inventory at least within a few metres from the emplacement horizon and certainly containment in the geological stratum or immediate rock mass where the repository is located.

The specific roles of the geological environment and of the engineered barrier system as functions of time are discussed in the following sections.

The changing emphasis over time may vary relative to protection from the three aspects of the hazard discussed earlier in Section 2.2.1: both internal (ingestion and inhalation) and external exposures from radiological components as well as any chemically toxic materials that may be present in radioactive waste and its packaging. Safety cases tend to emphasise doses from ingestion and inhalation of radionuclides. Many of the same time frame considerations – in terms of containment and isolation performance, and in terms of the longevity of the hazard – apply to external exposures to radiation. In safety cases, external irradiation is typically dealt with in human intrusion scenarios. Depending on the stability of the site under consideration (and, in particular, rates of uplift and erosion), external irradiation due to direct exposure to the waste may also become an important scenario at very distant times. A related issue is how to weight the significance, in choosing among candidate sites or at other decision points, if safety changes for a site over different times frames or relative to the different aspects of the hazard. For example, how does one choose between two sites or design options if both meet the minimum criteria yet one provides substantial containment for a few thousand years longer while, on the other hand, having greater potential for compromised isolation in the very far future due to uplift and erosion? Questions such as these are related both to the uncertainties of repository system evolution and to the interpretation of ethical obligations to future generations, and their resolution requires further discussion.

The chemical hazards associated with waste may or may not be addressed directly in safety cases alongside radiological hazards. In some national programmes, there are separate legal requirements, regulations or safety criteria (often over different time frames) that apply to the analysis of the chemotoxicity of the repository.

3.2.2 Isolation and protection functions of the geological environment

The isolation of radioactive waste from humans is essential given the long-term hazard due to its radiological and possibly chemical hazard potential (Section 2.2), and the potential for misapplication of the materials. Providing this isolation is a key safety function of the geological environment[13] in all disposal concepts that extends throughout the post-closure period – or at least for as long as geological stability can be assured (Section 2.4). Isolation is achieved by placing the waste deep underground in a location lacking potential resources and with all access routes to the repository backfilled and sealed. This screens humans in the surface environment from external irradiation and considerably reduces the risks of both intentional and inadvertent human disturbances and intrusion.

A well-chosen geological environment also provides chemical and physical conditions that are relatively stable over long timescales (Sections 2.3 and 2.4) – i.e. not subject to sudden or rapid detrimental changes – and thus protects the waste and the engineered barriers from various external phenomena, such as climatic events, climate change, erosion and other geomorphological processes, and favours their longevity and barrier performance (e.g. slow corrosion/dissolution processes). This is particularly important in concepts that place emphasis on a prolonged period of substantially complete containment in the engineered barrier system (Section 3.2.6).

3.2.3 Transport barrier function of the geological environment

In addition to its isolation role, the geological environment also provides a transport barrier that prevents or delays and attenuates the releases to the biosphere of any radionuclides from the repository. The geosphere can fulfil its role as a transport barrier in different ways. In the case of a salt deposit, the key feature is the virtual absence of water as a transport medium. In many other geological media, it is the slow movement of groundwater (in the case of some argillaceous media, leading to diffusion-dominated migration) and geochemical retardation or immobilisation, as well as physical retardation by matrix diffusion in the case of fractured media, that ensure long travel times and consequent radioactive decay for most radionuclides should they be released from a repository. These physical processes lead to a spreading of released radionuclides in time and space through diffusion, retention, hydrodynamic dispersion and dilution. They all serve to reduce the rates of release of any radionuclides to the surface environment, and consequently, the concentrations that might occur there.

The transport barrier function of the geological environment is provided throughout the post-closure period (again provided there is adequate geosphere stability). Partly in view of the fact that reliable prognoses regarding the future evolution of the geosphere can be based on an understanding of geological history that extends from the distant past (Section 2.4), some programmes focus at distant times exclusively on the geological environment to provide containment of radionuclides and to attenuate releases (this view is expressed, for example, in the French regulations DSIN 1991). It is, however, a latent function until such a time as radionuclides are released from the engineered barrier system. Its contribution to the safety case in different time frames thus depends on the performance of the engineered barrier system, which varies considerably between concepts, in part because of the differences in the expected performance of the geological barrier and the degree to which this performance can be quantified with confidence.

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[13] The broad safety roles of the geological environment are qualitatively similar in all concepts – see, for example, the NEA IPAG-1 exercise – (NEA, 1997), and, more recently, the first NEA AMIGO workshop (NEA, 2003b). AMIGO is an OECD/NEA international project on "Approaches and Methods for Integrating Geological Information in the Safety Case".

Those programmes in which the host rock essentially prevents advective transport – for example, those considering argillaceous sediments and salt – place emphasis on the geosphere as a transport barrier from early times, although a prolonged period of substantially complete containment and delayed release may nevertheless be provided by the engineered barriers. Those programmes considering saturated, fractured hard rocks, where the fractures provide potential pathways for radionuclide transport, tend to place greater emphasis on a prolonged period of containment by, and limited release from, the engineered barriers (e.g. the period of substantially complete containment by copper canisters in the Swedish and Finnish concepts for spent fuel disposal in fractured hard rock – Table 3.1), with a key role of the geosphere being to ensure engineered barrier longevity (i.e. the protective role of the geosphere – above). The transport barrier function of the geological environment remains latent, in some cases throughout the entire period addressed by the safety case (e.g. Box 3.1). This is consistent with the trend towards greater awareness of the difficulties in fully characterising heterogeneous host rocks, which has been noted, for example, in NEA (1999a; 1999b).

3.2.4 Roles of the engineered barriers

The engineered barrier system of a repository represents the man-made, engineered materials placed within a repository, including the waste form, waste canisters, buffer materials, backfill and seals. The NEA has recently reviewed the role of engineered barrier systems in different disposal concepts (NEA, 2003a).

For a given site, the implementer must design an engineered barrier system that is suited to the physical and chemical conditions at the planned disposal depth and is compatible with the waste types under consideration, including the thermal output of the wastes. The safety functions it provides should complement those provided by the geological environment, compensating as far as possible for any deficiencies or uncertainties that affect them. The engineered barriers should also be compatible with programme-specific constraints and requirements, such as requirements regarding monitoring, reversibility and retrievability.

The construction and operation of a repository inevitably perturbs the properties of the surrounding rock, primarily through the creation of underground openings and access routes. Thus, in most concepts a key role of engineered barrier systems, and a key consideration in designing their layout, is to limit preferential radionuclide transport to the surface along repository excavations and their associated mechanically disturbed zones, for example by the use of low-permeability backfill and seals and by avoiding by layout high hydraulic gradients that could drive water flow.

The emplacement of heat producing and sometimes chemically complex wastes can also disturb the surrounding rock. Disturbances can be thermal, hydraulic, mechanical and chemical in nature, and can in some cases involve coupled processes that are poorly understood. In order to mitigate the effects of uncertainties associated with thermally driven processes, engineered barrier concepts for spent fuel and vitrified high-level waste are generally designed to provide an initial period of substantially complete containment in canisters or waste packages over a time frame of several hundred years or more while heat output declines to a low level (Table 3.1 – see also Appendix 4, observations from responses to Question 9.2). This provides a relatively simple basis for safety over a time frame sometimes referred to as the “thermal phase”, in which the processes themselves may be complex, but have no impact on overall performance provided radionuclides are contained. It also means that when releases do eventually occur, they do so at times when the system is essentially in a steady state, or is at least evolving in a slower and better understood manner. This makes the safety case less sensitive to the uncertainties associated with the thermal phase.

A period of substantially complete containment is sometimes a regulatory requirement for spent fuel and high-level waste disposal:

- Finnish regulations for low- and intermediate-level waste (STUK, 2003) state that "*The engineered barriers shall effectively limit the release of radioactive substances from the waste emplacement rooms for at least 500 years*".
- The French RFS III,2f French Safety Rule (DSIN 1991) states that high-level waste packages should *prevent* the dispersal of radionuclides when the activity of short and medium-lived radionuclides is predominant (for intermediate-level waste, on the other hand, the waste package should *limit* the release of radionuclides on a period to be prescribed by the implementer).
- Swiss regulatory guidelines (HSK & KSA, 1993) state that "... *in the case of HLW disposal, there is a particularly high hazard potential during the initial phase (around 1 000 years). During this phase complete containment of radionuclides within the repository should be aimed at*".

Other engineered components may be designed to protect the waste packages or canisters and ensure their longevity, including, for example:

- use of a dense and plastic bentonite buffer around SF/HLW canisters, which protects the canisters against rock movements and the effects of microbial activity; and
- in the case of Yucca Mountain in the US, placing coverings (titanium "drip shields") over the waste containers, which are emplaced in open (meaning not backfilled) excavations in the unsaturated zone to protect against dripping water and rock-falls from seismic events.

In many repository concepts in saturated geological settings, following canister breaching and the ingress of water, spent fuel and vitrified high-level waste forms are likely to be highly stable in the expected reducing chemical environments, with dissolution requiring hundreds of thousands of years or more (although more conservative dissolution rates are often used in safety assessments). By contrast, in an unsaturated environment, chemical alteration of spent fuel and vitrified high-level waste following canister breaching might be more rapid, requiring hundreds of years for spent fuel and a few thousand years for vitrified high-level waste. At Yucca Mountain (United States), for example, to compensate for the relatively rapid potential alteration of the waste forms, materials have been selected for the waste containers that promise extremely long container life. This is achieved though the passive metal oxide layer that forms and is maintained on the surface of the containers as long as they remain in an oxidising environment.

Other programmes too have developed engineered barrier systems for spent fuel and vitrified high-level waste that delay and attenuate releases to the geosphere over periods far in excess of the thermal phase, via the durability of the canisters and/or the slow transport through a surrounding buffer material (often a plastic clay), providing defence in depth even for concepts in which the geosphere transport barrier is expected to be highly effective. Engineered barrier concepts for intermediate-level waste, on the other hand, typically place less reliance on the durability of containers. These may, for example, be fitted with vents to allow gases produced by the waste to be released so as to avoid over-pressurisation. Such vents may provide locations for water ingress and radionuclide release, and this is taken into consideration in the overall design of the concept and in the development of the safety case.

Table 3-1: **Expected periods of substantially complete containment by spent fuel and high-level waste canisters**

Canister materials	Expected period of complete containment[14]
Canister with copper shell and cast iron insert as defined in the KBS-3 Concept	> 10^6 years (> 10^3 years even for pessimistic assumptions regarding initial defects and subsequent evolution) [Finnish and Swedish programmes]
Carbon steel inner container with copper outer shell	> 10^5 years [Canadian programme]
Stainless steel with carbon steel insert	10^3 – 10^4 years [French programme]
Carbon steel	500 – 10^5 years [Belgian, Czech, Japanese, Spanish and Swiss programmes]
Ni-based alloy with stainless steel inside	> 10^4 years [US Yucca Mountain programme]

3.3 Regulatory criteria as a function of time

3.3.1 Quantitative and qualitative safety criteria and requirements

Regulations set the protection criteria, both quantitative and qualitative, that must be met by a geological repository and its components.

Over the course of time, it is generally not possible to completely exclude scenarios in which, for example, isolation of the waste is compromised or releases of radionuclides occur (even the most stable systems will eventually be subject to changes that may degrade their isolation and containment functions – see Sections 2.3 and 2.4). Thus, regulatory criteria have been developed against which the consequences of these scenarios can be judged. Regulations also take into account the fact that there are inevitable uncertainties in evaluating these consequences.

In the statements of the ICRP and the IAEA and in many regulations the primary principles and requirements to be met are qualitative, and include, for example, optimisation, good engineering and management practice and the establishment of a safety culture. These are supplemented by more quantitative protection goals. In the regulation of nuclear facilities, these goals usually take the form of dose[15] or risk criteria. In the case of geological repositories, quantitative criteria apply over time frames of at least 1 000 or 10 000 years and sometimes without time limit. However, as discussed in the following sections, other quantitative or qualitative criteria and requirements may be increasingly emphasised or take precedence in the longer term.

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[14] Assessments often consider cases or scenarios in which earlier releases occur, e.g. due to the presence of a small number of initially defective canisters, or the occurrence of less likely perturbing events such as igneous intrusion or seismic ground motion that is assumed to damage the underground system.

[15] More precisely, criteria are expressed in terms of the concept of effective dose equivalent. This provides a way of converting the complicated process of radioactive intake into a simplified concept of a uniform whole-body dose. It gives a common scale for comparison of the increased chances of harm (measured mainly by excess fatal cancers and hereditary disease) arising from different types of radiation exposure and different exposures arising to different organs.

Quantitative regulatory criteria generally relate to the performance of the disposal system as a whole. The detailed specification in regulation of requirements on system components is generally avoided; the current view is that this would unnecessarily reduce the flexibility of the implementer to adapt system components to the specific characteristics of the waste and the geological environment under consideration, and would potentially undermine the need for the implementer to take full responsibility for the safety case. Where regulations place requirements on system components, these mostly relate to geological stability and predictability (Section 2.4) and to the need for a period of complete containment by the engineered barrier system, in particular in the case of spent fuel and high-level waste (Section 3.2). Regulations may also require the use of "best available techniques" or BAT. For example, SSI (2000) requires that the repository should represent:

> *"the most effective measure available to limit the release of radioactive substances and the harmful effects of the releases on human health and the environment, which does not entail unreasonable costs".*

This approach is similar to that embodied in the concept of "constrained optimisation" as described in ICRP-81.

Compliance with quantitative criteria is generally tested by means of safety assessment modelling. For geological repositories, the strategic requirement for optimisation is generally considered satisfied if all design and implementation decisions have been taken with a view to ensuring robust safety both during operations and after repository closure.

3.3.2 Recognition in regulation of the impossibility of precise prediction

In testing compliance with quantitative criteria, regulators generally require the impact of uncertainties to be taken into account, although conservative assumptions may also be made in safety assessment modelling. The Swiss regulator, for example, states (HSK & KSA, 1993):

> "*When calculating dose or risk, the applicant has to give the possible ranges of variation of the relevant data. He also has to give the range of variation in the results following from these data. Conservative assumptions are to be made, where uncertainties remain.*"

In addition, estimates of the degree to which conservatism affects the results of analyses can be valuable in judging the meaning of these results.

The meaning of dose and risk in the context of the long-term safety case is also recognised as being different to that of doses and risks calculated over shorter time frames in the context, for example, of the operational safety of nuclear facilities. In operational safety assessment, a comprehensive range of credible situations can be identified and analysed in which real individuals may potentially receive an actual dose that can be controlled. The evaluation of actual doses and risks over longer timescales, however, would require knowledge of aspects of biosphere evolution and of future human actions and behaviour that is unattainable beyond a few decades to a few hundred years at most (Figure 2.3). Thus, precise prediction of doses and risks over long timescales is generally regarded as impossible. Furthermore, changes in the human species cannot be ruled out over the timescales considered in some safety cases – the oldest known anatomically modern human being lived in Africa about 200 thousand years ago – McDougall *et al.* (2005). The nature of the species that might be exposed to doses and risks is thus also uncertain over sufficiently long periods of time.

The ICRP has recognised, for example, in ICRP-81 (ICRP, 2000) that:

> *"Doses and risks, as measures of health detriment, cannot be forecast with any certainty for periods beyond around several hundreds of years into the future ..."*

ICRP-81 goes on to state:

> *"Instead, estimates of doses or risks for longer time periods can be made and compared with appropriate criteria ... in a test to give an indication of whether the repository is acceptable given current understanding of the disposal system. Such estimates must not be regarded as predictions of future health detriment."*

and:

> *"In a long-term radiological assessment, doses or risks are calculated under reasonably selected test conditions as if they were doses or risks as defined in the Commission's framework. In the Commission's view they should be considered as performance measures or 'safety indicators' indicating the level of radiological safety provided by the disposal system."*

Calculated values of dose and risk are therefore viewed in regulations not as predictions but rather as indicators or measures of protection that are used to test the capability of the system to provide isolation of the waste and containment of radionuclides (the "dose" that is being calculated is what radio-protectionists refer to as "potential dose"). These indicators are to be evaluated on the basis of models that include certain stylised assumptions, in particular regarding the biosphere and human lifestyle or actions.

In evaluating compliance with regulatory criteria, or in formulating these criteria, extreme scenarios or parameter distributions can generally be assigned less weight. This is, for example, inherent in criteria expressed in terms of risk. In the US, regulations use the standard of "reasonable expectation", also to discourage reliance on extreme scenarios or parameter distributions as a way to deal with uncertainties, which may result in overly conservative estimates of potential consequences as uncertainties become large (Appendix 4, observations from responses to Question 8.1). The US NRC states that (US NRC, 1998):

> *"Although the Commission does not require an "accurate" prediction of the future, uncertainty in performance estimates cannot be so large that the Commission cannot find a reasonable expectation that the post closure performance objectives will be met."*

In its draft rule for Yucca Mountain, the US EPA considers the implications of applying the reasonable expectation standard over a time frame of up to a million years (Section II.B in US EPA, 2005).

Finally, the ICRP has recently developed a new draft recommendation, which suggests a reasonable approach to selecting human characteristics and habits necessary for exposure estimation without focussing on extreme behaviour (ICRP, 2005a).

3.3.3 Overall time frames considered in regulations

Some national regulations or regulatory guidelines contain no explicit guidance on the overall time frame over which protection objectives apply. In countries such as Hungary and the Czech Republic, it is a legal or regulatory requirement that safety must be assessed over the lifetime of the facility, which is defined, for example, in terms of the declining activity of the waste. National regulations such as those in Canada (CNSC, 2004), France (DSIN, 1991) and Switzerland (HSK & KSA, 1993) state or imply that protection objectives expressed in terms of dose and risk apply without time limit or that compliance should be shown up to the time of maximum consequences, which must be determined by the implementer (Appendix 4, observations from responses to Questions 2.1 and 2.2).

In other regulations, quantitative criteria apply over a limited time frame (and can vary with time within that time frame, see Section 3.3.2). In Sweden, for example, guidance from the Swedish Radiation Protection Authority (SSI) states that risk assessment of repositories for spent fuel and long-lived wastes should cover at least 10^5 years or one glacial cycle, but should continue for as long as the analysis gives useful information for improving the repository, up to a maximum of a million years. No account need be given of the period beyond a million years, even if peak calculated doses or risks occur in this time frame and the remaining activity is such that there is still the potential for the repository to cause harmful effects (SSI, 2005). In Finland, some discussion of safety is expected for the time frame beyond a million years, but this can be of a more qualitative kind than at earlier times, referring, for example, to the much reduced radioactivity of the waste (STUK, 2001). The draft EPA regulations for Yucca Mountain in the US (US EPA, 2005), on the other hand, recognise that it may not even be meaningful to talk about the radiological protection of humans in a time frame beyond a million years (see Section 3.3.1), and, as in Sweden, no discussion of safety is required by the draft regulations in this time frame.

Regulations in the United Kingdom, while not specifying a particular time frame for assessment calculations, recognise that in the very long term, irreducible and site-dependent uncertainties provide a basis for a natural limit to the timescale over which it is sensible to attempt to make detailed calculations of disposal system performance (Environment Agency *et al.* 1997) (see Appendix 4, observations from responses to Question 7.2).

3.3.4 Time-varying regulatory criteria and requirements

There are broad similarities in the quantitative safety criteria set by all national regulations over the post-closure time frame up to about 10 000 years – all are expressed as dose or risk limits or guidelines, although there are some differences in the numerical limits or guidelines set. Differences, however, arise at later times in that, as noted above, some regulations continue to express the level of protection that is required as constant numerical criteria for dose and risk that apply, in principle, for "all time", whereas some recent regulations specify different criteria in different time frames, in recognition of the fact that increasing uncertainties may make calculated dose or risk less meaningful. The selection of safety indicators for evaluation in safety assessments, which may be either a result of regulation or a decision of the implementer to evaluate complementary indicators in addition to those required by regulation, is discussed in Section 5.2.4.

The specification of different types of criteria in different time frames is a feature of the US EPA draft rule for Yucca Mountain, which specifies (US EPA, 2005):

- an individual protection standard (dose from repository system not disturbed by human intrusion, with different standards set for 10 000 years and a million years – see below);
- a human intrusion standard, in which the time of package failure and of subsequent dose from the intrusion scenario determines the dose limit used for the standard; and
- a groundwater protection standard – levels of radioactivity in a representative volume of groundwater – for 10 000 years (here, the time frame is set for consistency with the national policy for resource protection embodied in the U.S. Safe Drinking Water Act).

As another example, Finnish regulations (STUK, 2001 – see also Appendix 4, Box A4-1) distinguish between the "environmentally predictable future" (several thousand years), during which conservative estimates of dose must be made, and the "era of extreme climate changes" (beyond about ten thousand years) when periods of permafrost and glaciations are expected, and radiation protection criteria are based on constraints on nuclide-specific activity fluxes from the geosphere ("geo-bio flux" constraints).

In the Finnish case, the setting of different criteria in different time frames reflects a view that it is not justified to require a demonstration of compliance with any given limits beyond the time when a given safety indicator can be evaluated with an appropriate degree of confidence. As discussed in Chapter 5, there are safety indicators available that are less affected than dose and risk by some uncertainties (e.g. uncertainties in the evolution of near-surface aquifers and the biosphere), although they also provide a less direct indicator of potential harm. In time frames when such uncertainties become large and difficult to quantify, for example when the surface environment could be affected by major climate change due to glacial cycling, it is considered by some regulators to be more appropriate to give criteria in terms of these alternative indicators.

Setting quantitative criteria in terms of different safety indicators in different time frames should not necessarily be construed as indicating that different (lesser) levels of protection are acceptable at later times. Rather, it is an acknowledgement of the limitations of what is possible in, and what is reasonable to expect from, safety assessment modelling carried out by the implementer and an acknowledgement that increasing uncertainties over long timescales may make some indicators (specifically those relying on detailed calculations) less meaningful. Although the safety indicators specified in regulations may vary with time, the underlying level of risk identified as an objective could remain the same, if the principle of intergenerational equity is interpreted to mean that responsibilities of the present generation extend equally and indefinitely into the future. In Finnish regulations, for example, in setting geo-bio flux constraints beyond 10 000 years, the underlying risk limit is unchanged. The geo-bio flux constraints, which are chosen to be consistent with this limit, are based partly on natural radionuclide fluxes and partly on biosphere modelling, both of which are specific to the Finnish situation. Thus, uncertainties regarding human lifestyles, biosphere pathways, aquifer dilution and dose conversion coefficients are not truly circumvented by framing criteria in terms of geo-bio flux constraints. Rather, the regulator has, in effect, taken responsibility for dealing with these uncertainties by specifying stylised assumptions in a time frame when it is considered that actual human lifestyles, biosphere pathways, aquifer dilution and dose coefficients cannot be known, or even bounded, with an appropriate degree of confidence. In other countries, stylised modelling is also employed, but it is a matter for the implementer to decide upon and justify the stylised assumptions made. In Switzerland, however, regulations support biosphere stylisation with an instruction to calculate the doses assuming reference biospheres and a population group with realistic living habits, as seen from the current point of view (HSK & KSA, 1993).

In Swedish regulations, although there is also no adjustment of the risk standard with time (at least up to a million years, which is the time frame to be addressed in the safety case), regulations acknowledge that, due to increasing uncertainties, the weight given to risk and dose estimates for compliance demonstration decreases with time, and the focus of compliance demonstration shifts to other measures, such as complementary safety indicators and the use of "best available techniques" or BAT. The regulator will determine by qualitative reasoning whether appropriate indicators and "best available technique" have been applied.[16] In the United Kingdom, the Radioactive Substances Act of 1993 incorporates a similar concept under the terminology "best practicable means" (BPM). Such requirements are consistent with the view of the ICRP, as set out in ICRP-81 (ICRP, 2000), that a series of technical and managerial principles, such as sound engineering principles and a comprehensive quality assurance system, are key elements to enhance confidence in long-term safety.

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[16] In the case of "best available technique", this may in practice mean that all choices that are made regarding the system and its analysis must be explained, shown to be reasonable and put into context of how they affect safety and the safety case.

The ICRP has recently produced a draft recommendation in which it states that predicted doses should not play a major part in decision-making processes for planned, regulated sources or exposure situations (taken to be a licensed facility, such as a nuclear power plant, a factory producing radio-pharmaceuticals, or a hospital – geological disposal is not specifically mentioned) over a period of more than a few generations, in view of the difficulties in predicting both the individual doses and the size of exposure population, and also considering that the relationship between the dose and detriment may no longer be valid for future populations. It suggests using a system whereby decreasing weight is assigned to calculated doses with increasing time (ICRP, 2005b).

Similarly, there are arguments that could be used to justify a time varying weighting to the value of dose or risk limits, resulting in earlier, more restrictive limits and later, less restrictive limits. There is ongoing debate in this area (see e.g. the ongoing work in RWMC's Long-Term Safety Criteria task group). In Section 2.1, for example, it is noted that increasing uncertainties with time may mean that the capacity of the present generation to assume responsibility for the protection of future generations changes with time. An emphasis on nearer-term concrete risks over longer-term more hypothetical risks is also a part of the chain of obligation principle proposed by the US National Academy of Public Administration. Although such an approach is not currently taken in any national regulations, the US EPA in its draft rule for Yucca Mountain proposes a dose standard of 0.15 mSv per year for times up to 10 000 years and a higher (though still protective) standard of 3.5 mSv per year from 10 000 to a million years based on background radiation differences now experienced regionally by existing populations (US EPA, 2005). This higher standard may be seen as a combination of a natural flux comparison with a dose rate criterion.

Some national regulations require a more detailed description and modelling of system evolution in earlier compared to later time frames, and a more thorough investigation and treatment of uncertainty (Appendix 4, observations from responses to Questions 7.1, 7.2 and 8.1). In Sweden, for example, regulations require a detailed and quantitative assessment of consequences to humans and the environment for the first thousand years, but an evaluation based on illustrative scenarios (and an increasing emphasis on BAT) thereafter. In some other cases, beyond a certain time, emphasis may shift to most likely possibilities, with unlikely possibilities excluded from assessment modelling because their assessment is considered to become unduly speculative given the poorly quantifiable uncertainties; the omission of outlying possibilities at distant times is sometimes justified by the reduced radiological hazard presented by the waste.

Overall, it may be said that safety criteria are required that, while protective for successive future generations, do not place unreasonable demands on system siting and design and on assessment of long-term safety. A balance (which can vary between national programmes) needs to be struck between different principles, and a realistic view taken about what is achievable in practice.

4. NATIONAL POLICIES IN THE PLANNING OF PRE- AND POST-CLOSURE ACTIONS

4.1 Impact of an extended open period on post-closure safety

In their planning of repository construction, operation and closure, some programmes are considering concepts that include an extended "open period", in which the waste is kept readily retrievable and there is flexibility in the timing of any decision to backfill and seal the underground openings in which the waste is emplaced, which may be delayed perhaps for some hundreds of years (Appendix 4, observations from responses to Question 5.1b). Such concepts aim to combine, to some extent, the positive aspects of geological disposal, in terms of passive safety and security, and long-term storage, in terms of flexibility in decision-making.

Currently, national programmes vary considerably in the degree to which plans have been made for an extended open period. In Canada, NWMO has recommended Adaptive Phased Management, in which there is provision for retrievability of used fuel for a period lasting until such time as future society makes a decision on final closure, and on the appropriate form and duration of post-closure monitoring (NWMO, 2005). In the United Kingdom, a care and maintenance period of up to 300 years is currently foreseen, during which the facility would be open and the wastes monitored. In the United States, an open period of between 100 and 300 years is foreseen. In all these countries, the exact duration of such a period is regarded as being a decision for future generations. In planning how to implement an extended open period, including the time frame over which it will continue, the flexibility that this provides to future generations needs to be balanced against any detrimental effects that this period could have on long-term safety and the safety case.

For example, an unsealed repository would require active controls to guard against unauthorised access to the disposed materials. Furthermore, if left without backfilling, underground tunnels are likely to require continual monitoring and maintenance to guard against tunnel collapse, which, if it were to occur, could potentially make final backfilling difficult. The prospect of potential societal instability, which could lead to lapses in maintenance and security or even the neglect and premature abandonment of the disposal system, increases with time and may certainly be significant when considering safety over a time frame of centuries. To some extent, these concerns can be addressed by the design of the repository. For example, the concept of monitored long-term geological disposal considered in Switzerland for the disposal of spent fuel, vitrified high-level waste and long-lived intermediate-level waste involves an extended period of monitoring, during which retrieval of the waste is relatively easy, and the emplacement of a representative fraction of the waste in a pilot facility to test predictive models and to facilitate the early detection of any unexpected undesirable behaviour of the system should this occur. The pilot facility and its access routes are arranged in such a way that the facility can continue to be monitored for a long period after closure of the main facility. Both the main facility and the pilot facility should not represent a significant risk if, during a time of crisis, they should be abandoned without the access routes being closed according to plan (Nagra, 2002).

The safety case must take into account changes resulting from any open period on long-term performance (Appendix 4, observations from responses to Question 5.1a). The excavation, drainage and ventilation of underground openings, for example, inevitably perturb the geological environment of a repository. The engineered barrier system may also change, albeit only slightly in many cases, in the period between its emplacement and repository closure, and the processes bringing about these changes may be different to those operating post-closure. Some of the changes may be detrimental to long-term safety, or may at least complicate the safety case. The magnitude of the changes, and duration of transient perturbations, can sometimes increase with the duration of the open period. For example, in the case of a saturated host rock, drawdown of waters closer to the surface, up-coning of deep groundwaters, a reduction of the formation pore pressure at repository depth, and some de-saturation of the rock around the repository may all occur during the open period. These disturbances are likely to be reversible, but over timescales that may be greater for a prolonged pre-closure open phase than for a short one. A prolonged open period may also increase the probability that extraneous materials will be introduced into the repository and subsequently overlooked (e.g. oil spills)[17] and also increases the likelihood of accidents and unexpected events (e.g. rock falls) in general.

It is widely acknowledged that the disturbances caused by any open period on the safety-relevant characteristics of the system must be assessed as part of a safety case, although many can be excluded from detailed consideration, e.g. in safety assessment calculations, due to their limited impact or reversibility over short timescales.[18] In the case of the fractured hard rock at the Olkiluoto site in Finland, for example, the formation pore pressure at repository depth is expected to recover within a couple of years of backfilling and sealing the facility and the salinity distribution to recover within a few hundred years (Vieno *et al.*, 2003). A few perturbations may be irreversible or reversible over a longer timescale. In the case of the Callovo-Oxfordian clay being considered as a potential host rock in France, disturbances to the stress field of the site will eventually return to a state of equilibrium, but this is expected to take up to several hundred thousand years. Some irreversible or slowly reversible perturbations may need to be taken into account explicitly in the safety assessment calculations. An example is the formation of excavation-disturbed zones around underground excavations, which may have hydraulic conductivities that are orders of magnitude higher than the undisturbed rock and, in the case of many hard rocks (with the exception of salt), can persist with little change for very long times. The positive outcome of the recent peer review of the French Dossier 2005 Argile (Andra, 2005) also shows that safety cases have and can effectively address the potential effects on long-term safety of an open period.

Ensuring that there is no unacceptable long-term impact of the pre-closure phase on post-closure safety is widely seen as an objective in the planning of repository construction, operation and closure. The specific perturbations that need to be avoided can depend strongly on the specific barriers and safety functions provided by the system and the degree to which these are emphasised in the safety case. For example, if the diffusive transport barrier provided by a layer of plastic clay host rock is considered a key element of the safety case, then an important consideration is the avoidance of mechanical and chemical perturbations that could degrade this barrier. The repository may be designed to mitigate the potential impact of disturbances caused by any extended open period. For example, in the case of repositories for spent fuel and vitrified high-level waste in a saturated rock, steel canisters,

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[17] Establishing a "safety culture" that seeks continual improvement and requires all potentially important process-influences of an introduced material, design change, or action to be analysed and documented, and applying quality assurance procedures during operation and any open period, are important in reducing this probability.

[18] Although understanding of processes occurring in the pre-closure phase and safety assessment modelling of the impact of the pre-closure phase on post-closure safety may require more attention in some concepts, this is not widely seen as an area critical to the safety case (e.g. NEA, 2005).

if used, are designed with a corrosion allowance that takes account of uncertainties in the duration of the resaturation period, during which oxidising conditions may prevail and more rapid corrosion processes operate. A concern being addressed in most repository programmes involves the introduction of bacteria and their food sources during the construction and operational phases. This could lead for example to transient increases in corrosion rates. This type of uncertainty is also typically managed through the use of a robust container that can meet reliability targets even with a transient period of accelerated corrosion.

In view of the prospect of potential societal changes and of potentially detrimental perturbations occurring during or as a result of any open period, it may be prudent, from the point of view of safety, to work towards closure soon after completion of waste deposition. A shorter open period may also simplify the making of the safety case by reducing the time that the system is subjected to sometimes poorly understood transient processes, thus simplifying the analysis and description of repository evolution. These considerations have to be balanced against the ethical principle that future generations should be allowed flexibility in their decision-making, considerations of public perception and confidence, and programme-specific factors such as policies on retrievability and post-emplacement, pre-closure monitoring, which may require a more prolonged open period (see the discussion of ethical considerations in Chapter 2), or the views of the local community.

4.2 Monitoring and post-closure actions

The roles of both pre- and post-closure monitoring have been reviewed in NEA (2004c). There is a broad consensus that pre-closure monitoring of a wide range of parameters within and around a repository is an essential part of compiling a database for repository planning and for developing the safety case that supports decisions on implementation and closure. It may also support construction and operation, enabling any problems to be detected so that corrective actions can be taken. The extent and duration of the post-closure monitoring that will be undertaken is being discussed in many national programmes and internationally, and may in practice be decided as the licensing process proceeds.

In addition to monitoring, further passive and active measures may be required in the post-closure period.[19] Passive measures include for example record keeping, government ownership and land use restrictions, the construction of durable surface markers, and other measures of preserving knowledge about the location, design and contents of the disposal system. Active measures are those requiring continuous human oversight, such as conducting security patrols, or restricting access to a site (largely to satisfy security goals and IAEA safeguards requirements). The requirement for passive safety (Section 3.1.2) means that safety must not, in the long-term, depend on active measures, although they are not excluded.

With respect to timescales and the safety case, the main issues of concern are:

- How long should active measures, including monitoring, be maintained?
- What credit if any can be taken for both active and more passive measures in the safety case?

There are differences in the degree to which national regulations address these questions. In some cases, regulations indicate (i) the time frame over which monitoring, control and record keeping should be maintained, and/or (ii) the time frame over which human intrusion can be excluded in a safety case as a result of such actions. Examples are given in Table 4.2. In other cases, these time

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[19] Although such measures may operate after closure, they may be initiated (or plans drawn up) at earlier times.

frames are left to the implementer to determine and justify, and may then be formally decided in the course of the licensing process.

Table 4.2: **Examples of regulatory positions regarding the time frames for monitoring, control and record keeping (see Appendix 4, observations from responses to Question 5.2a)**

Issue	Regulations and regulatory guidelines	Time frame
Minimum period that active institutional control should be maintained (including monitoring of environmental conditions, e.g. concentrations of radioactive isotopes).	Hungarian regulations	0-50 years
Period beyond which no credit for active institutional control may be taken in a safety case	US EPA	100 years (the controls themselves must be maintained for more than 100 years if possible)
Period during which passive institutional controls are required, including monuments, markers and multiple record retention systems	US EPA and NRC	As long as achievable
Period of passive institutional control during which records can assumed to be preserved and probability of human intrusion is thus low	French regulatory guidance	0-500 years
Period during which inadvertent human intrusion can be excluded due information conservation	German Draft Criteria	0-500 years

The detection by monitoring of changes that could lead to decisions to intervene in the repository system in some manner is extremely unlikely, because of the nature of the expected processes and the ability to monitor changes in them. Post-closure monitoring may nevertheless be required by regulations as an element of confirming good engineering practice. Furthermore, there is a small but non-zero probability that detected changes could lead to decisions to intervene in the repository system in some manner, including removing material from it to process or dispose of elsewhere. Even if, as expected, monitoring shows that there are no significant deviations from the expected evolution of the system, this demonstration may be of value in allaying concerns of the local population regarding safety.

In the interests of providing defence in depth, as well as for public reassurance (see below), it seems reasonable that a target should be that post-closure controls and monitoring are maintained for as long as reasonably possible, taking into account the demands that this may place, for example, on funding and other resources. As long as post-closure controls are maintained, there is little possibility of inadvertent human intrusion into the repository. On the other hand, in order to take credit for these actions in a safety case, it must be argued that society will have the means and motivation to carry on with post-closure controls in the future. Given the prospect of societal changes and the possibility that the priorities of future generations, e.g. with respect to funding allocation, may be different to those of today, such credit cannot be taken indefinitely.

A cautious approach requires that active control of a site cannot be assumed in safety assessments or safety cases for more than about a hundred years at most (Appendix 4, observations from responses to Question 5.2b). It is reasonable to assume that records will be kept for longer than this, perhaps a few hundred years, and that this will also make inadvertent human intrusion less likely. For example, the 500 year period during which, according to Draft German Criteria, inadvertent human intrusion can be excluded due to information conservation is supported by the existence of mining archives of a similar age to this in Germany, which are still being used today (GRS-A-2990)[20]. As a further example, the French Academy, which was established in 1635 for the governance of French literary effort, grammar, orthography, and rhetoric, has succeeded in maintaining its institutions and in transmitting its entire legacy over the intervening 350 years. Historically, some systems of record keeping have been maintained for still longer periods. For example, the Domesday Book, which is a record of land and population in England created about 1 000 years ago, is still accessible today.

An example of current record keeping for a nuclear waste management facility is the preservation of records of the Centre de Stockage de la Manche, a near-surface repository in North West France managed by the French National Agency for Radioactive Waste Management (Andra). Detailed records are kept both at the site and in the French National Archives. Use of special media, such as archival paper, is expected to permits these records to be preserved for from three to five centuries. Duplication of the records at regular intervals may be considered, which could potentially extend the conservation period. Durable markers for geological repositories may remain for longer still (perhaps thousands of years). With increasing time, however, it becomes increasingly uncertain whether the messages that records or markers are designed to convey will be understood by humans. Thus, no credit is taken for such measures in averting or reducing the likelihood of human intrusion in safety assessment beyond around a few hundred years.

In many countries, the public is seen as favouring disposal systems that, although passive, would allow remedial actions to be taken if monitoring indicates unacceptable, anomalous evolution. The slow evolution of many key processes, however, sets limits on what can be observed through practical monitoring programmes. As pointed out in NEA (2004c), direct demonstration of repository functions or the detection of failures would require the development and testing of new technologies.

There is consensus that no monitoring or other post-closure actions should be undertaken that could jeopardise the primary objectives of geological disposal, i.e. the isolation of waste and the containment of radionuclides (Appendix 4, observations from responses to Question 5.2b). This is clearly not an issue for remote techniques, e.g. satellite surveillance, aerial photography, microseismic monitoring. However, where intrusive monitoring techniques are proposed (e.g. sampling groundwater for subsequent chemical analysis), a key consideration is that they should not interfere with the operation of the repository safety functions. For example, US regulations for geological disposal of long-lived waste require that monitoring may not "jeopardise the containment of waste" (EPA generic regulation 40 CFR Part 191, which is applied to the Waste Isolation Pilot Plant).

Any decision to carry out post-closure monitoring should not be seen as suggesting that the safety case is judged unreliable by either the implementer or regulator. Although monitoring could, in principle, allow remedial actions to be taken if desired, this possibility should not form part of the long-term safety case (Appendix 4, observations from responses to Question 5.2b). This is because, in order for a repository to receive the required licences, the long-term safety case should have

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[20] www.rskonline.de/stellungnahmen/sicherheitskrit-endlager-rsk-ssk.pdf. (see p. 86)

demonstrated that there are no reasonably possible situations that would require post-closure remediation.

While the direct contributions from institutional controls to the safety case may be limited, and future enforcement mechanisms cannot be envisioned with certainty, requirements for such controls to continue for long periods are seen as a possible means not only of averting human intrusion, but also of improving societal acceptance and confidence in the disposal system. US regulations, for example, require active controls to be maintained "for as long a period of time as is practicable after disposal" and for monitoring to continue "until there are no significant concerns to be addressed" (Sections 14a and 14b of the EPA regulation, 40 CFR Part 191, applied for the Waste Isolation Pilot Plant – WIPP). The fact that the implementer must take concrete actions in the immediate future – including plans for passive controls, and establishing funding mechanisms – may provide some reassurance to the public of a commitment to ongoing stewardship at the site. This is analogous to requirements for nuclear safeguards, which require controls that are not time limited.

5. DEVELOPING AND PRESENTING A SAFETY CASE

5.1 Understanding how a repository and its geological environment evolve

5.1.1 Relevant events and processes

Events and processes varying widely in their rates, timing, likelihood of occurrence and impact affect the evolution of a repository and its environment. The identification of relevant events and processes is generally regarded as tasks for the implementer, although regulators may specify certain, sometimes site- or concept-specific events and processes that should, as a minimum, be considered for inclusion in a safety case, based on their own understanding and possibly as a result of dialogue with implementers (Appendix 4, observations from responses to Question 6.2a). Examples are:

- major climate change (either natural or anthropogenic);
- exceptional vertical geological movements;
- long-term seismic activity;
- volcanism; and
- releases of radionuclides affected by human actions.

Other criteria may also be applied to establish the boundaries of expected performance or the relevant processes to be included. For example, US NRC regulation 10 CFR Part 63 114 (d) and (e) (US NRC, 2001) gives screening criteria, in terms of a probabilities and consequences of occurrence, that are used to identify events that can be excluded. According to this regulation, which is specific to Yucca Mountain, the implementer should (i), consider only events that have at least one chance in 10 000 of occurring over 10 000 years (i.e. a probability of greater than 10^{-8} per year), and (ii), evaluate in detail specific features, events, and processes if the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, would be significantly changed by their omission.

5.1.2 Empirical basis for understanding long-term evolution

The long timescales addressed in safety cases mean that slow processes and low probability or infrequent events generally need to be considered. Direct observations of the events and processes affecting the long-term evolution of a repository and its geological setting in the laboratory or underground are, however, generally limited to a few years or a few decades at most.

In the case of the geological environment, observing processes and events such as igneous intrusion and glaciation in the repository setting may not be practical. Thus, statements regarding the possible future evolution of the geological environment are based largely on an understanding of site-specific geological history that extends from the distant past. For example, diagenesis has been slow in Boom Clay for the past 30 million years and Yucca Mountain has remained essentially unchanged for several million years (Appendix 4, observations from responses to Question 4.1). This understanding is complemented in some cases by information from analogous sites elsewhere.

Statements regarding the possible future evolution of the engineered barriers are generally based on system understanding and process models supported by relatively short-term laboratory and field experiments. The conditions under which experiments are performed can be selected to accelerate some processes of interest. Iron-clay interactions are, for example, too slow to be observed in the laboratory at the repository temperature, but are observable at higher temperatures. As a further example, glass dissolution in water may be accelerated if the concentration of silica in the water is kept low. In order to use the results of such experiments over timescales that are longer than the experiments themselves, either it must be possible to deduce the extent to which the process will be slowed under repository-relevant conditions, or the observed (accelerated) rates of detrimental processes can be used directly as a basis for conservative assessments of evolution. In either case, evidence may be needed that to support a position that there are no phenomena that are latent in the short-term experiments but may significantly and detrimentally affect, for example, the degradation rates of system components, in the longer term.

Natural and anthropogenic (human artifact) analogues can also provide evidence for the long-term stability of engineered barrier components and may overcome some of the limitations of temporal (and spatial) scale that are inherent in shorter-term and smaller-scale experiments. Analogues exist that provide information on the long-term behaviour of materials such as uranium, glass, copper, iron, nickel, chromium, bentonite and cement, as well as a range of rock types, complementing the data obtained from laboratory studies, site-characterisation and experimental studies in underground rock laboratories. It is a view of some organisations that a more widespread use of analogues would be justified (see Appendix 4, observations from responses to Question 9.3 – which also gives further examples of the use of analogues). They can, however, have significant limitations in that direct information on analogue systems is only available for one "snap shot" in time – the present. The initial conditions and the external processes that have affected the evolution of the analogue are often uncertain, limiting its use to qualitative, but important, observations on how, for example, physical components or processes are likely to behave in a comparable natural setting.

Table 5.1 illustrates some of the diverse types of evidence and argument that can support the stability of key system components and can be used to characterise the processes that affect their evolution.

5.13 Uncertainties in system evolution

The rates, timing, likelihood of occurrence and impact of the events and processes that affect the evolution of a repository and its environment are subject to differing degrees of uncertainty which may also vary with time. In developing a safety case, these uncertainties must be characterised as far as possible along with the events and processes themselves.

Table 5.2 shows examples of some of the main sources of uncertainties that were identified in the Swiss Project Opalinus Clay (Nagra, 2002), the system components that these uncertainties affect, the timescales over which perturbations to the system might occur, and how these perturbations were treated in the safety case. Examples of uncertainties from French Dossier 2005 Argile (Andra, 2005a-c) are shown in Table 5.3. Finally, Table 5.4 shows examples of some of the main sources of uncertainties that were identified in the three discrete post-closure time frames that were distinguished in the Belgian Safety Assessment and Feasibility Interim Report (SAFIR 2) for spent fuel and vitrified high-level waste disposal (ONDRAF/NIRAS, 2001).

Sensitivity analyses are often used to identify the most sensitive parameters across their respective ranges of uncertainty in particular time frames (Appendix 4, observations from responses to Question 8.2a). The most important uncertainties are clearly those affecting features and processes that contribute to the safety functions and that constitute basic arguments for safety in the safety case, such as, for example, the canisters in the case of the KBS-3 concept considered in Sweden and Finland or the host clay formation in SAFIR 2, in Dossier 2005 Argile and in Project Opalinus Clay (Nagra, 2002) (these key features and processes are termed the "pillars of safety" in Project Opalinus Clay). As described in Section 3.2, the emphasis placed on different barriers and safety functions, and hence the relative importance of associated uncertainties, can vary across the overall time frame addressed in the safety case.

Table 5.1: **Types of evidence and argument and examples of their application**

Types of evidence and 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 or processes	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; stability of various natural metals in specific environments – e.g. existence of native copper in fields in the Upper Peninsula of Michigan, US, for hundreds of thousands of years (see also Section 5.4.5 for further example).
Thermodynamic arguments	Stability of copper, which is used as a canister material in some designs, in reducing environments such as deep granite formations and groundwaters.
Kinetic arguments	Corrosion rate of iron, which is also a canister material in some designs.
Mass-balance arguments	Potential for chemical alteration (illitisation) of bentonite; rate of copper corrosion; range of alkaline plume into (clay) host rocks.
Anthropogenic analogues	Steel corrosion in industrial applications, industrial and government facilities with radioactive contamination.
Natural isotope profiles in some argillaceous rocks, groundwater ages and palaeo-hydrogeological information in general	Rate of groundwater movement and long-term stability of the geosphere as a transport barrier.
Laboratory experiments	Laboratory studies of, for example, glass dissolution, spent fuel dissolution, and barrier-metal corrosion under repository relevant chemical and physical conditions.
Underground rock laboratory experiments and observations	Simulation of effects caused by emplacement of radioactive waste (heat, radionuclide release, mechanical impact (see Kickmaier & McKinley 1997 for further examples).
Natural analogues for climate change	Analogues of possible future climate conditions at a site e.g. tundra; Devil's Hole calcite cores; ocean sediment cores, and Siberian ice cores; ostracod species succession and dating and packrat midden seeds and dates, as lines of evidence for timing and intensity of past climate changes.
Detailed modelling studies	Groundwater flow and radionuclide transport; likelihood and consequences of earthquakes or volcanic events.

Table 5.2: **Examples from the Swiss Project Plains Clay of some key uncertainties, the system components that these uncertainties affect, the time frames over which perturbations to the system might occur, and how these perturbations were treated in the safety assessment**

Source of uncertainty	**System components affected (incl. biosphere)**	**Time frames when relevant**	**Treatment**
Climatic effects			
Effects of glaciation	Biosphere, geosphere plus potential for transport along tunnels/ramp/shaft	> 10^4 years (timescale to next glacial period)	Assumed negligible in the Reference Case. Alternative case considers glacial induced flow in host rock.
Geological characteristics			
Transport characteristics of confining units above and below Opalinus Clay host rock	Geosphere	> 105 years (approximate minimum transport time through Opalinus Clay host rock)	Transport times through confining units conservatively neglected in Reference Case, but considered in an alternative conceptualisation.
Spent fuel (SF) and vitrified high-level waste (HLW) near field			
Extent and effects of bentonite thermal alteration	Inner part of bentonite buffer	Times beyond SF/HLW canister breaching time (104 years in Reference Case)	Assumed negligible in the Reference Case. Alternative case considers limited altered layer around canisters.
Glass dissolution rate	Waste matrix	Times beyond HLW canister breaching time up to time of complete waste form dissolution	Reference Case rate is considered realistic. Pessimistic increased rates considered in deterministic uncertainty analyses.
Biosphere			
Possibility of alternative discharge areas	Biosphere	Timescale of geomorphological change; i.e. times beyond about 104 years	Stylised-different geomorphological situations assumed to exist for all time.
Human actions			
Deep groundwater extraction	Biosphere plus confining units	All times following loss of records of repository and time needed for radionuclides to break through (near field, geosphere)	Assumed not to occur in Reference Case. Possibility considered in one realisation of the alternative scenario addressing release affected by human actions.

Note: The Reference Case is a model realisation of the evolution of the system, generally based on the expected evolution of the system components.

Table 5.3: **Uncertainties and timescales – examples from Dossier 2005 Argile**

Uncertainties regarding the behaviour of the repository over periods (up to a million years) are significant. Feedback on the evolution of natural or artificial systems on timescales of hundreds of years is limited to archaeological analogues, or to natural analogues that in turn give access to periods representative of geological timescales. But this does not mean that these uncertainties cannot be mastered with a sufficient degree of confidence. They must be tackled in a very systematic way, their effects analysed and taken into account in assessments.

Uncertainties are not the same from one period to another one, nor the components of the repository or its environment that are considered. Thus, by way of example:

- in the near field, i.e. in the immediate environment of the repository structures, uncertainties regarding the behaviour of the materials and the rock are going to decrease over time, when thermal, mechanical and hydrological processes due to disturbance of the repository dwindle or reach equilibrium. However, the time of attaining equilibrium and the exact nature of this equilibrium are subject to uncertainties;
- uncertainty regarding the surface environment and the surface layers of the geosphere will increase overall, especially when major climatic changes such as periodic glaciations are included in the assessment.

In the particular instance of material behaviour in the broad sense (including rock), it is possible to obtain or produce samples representative of most of the repository components (waste matrix, bentonite, concrete, etc.). Generally, it is also possible to place these samples in experimental conditions representative of those expected in the repository (in terms of pH, Eh, etc.) given the relative homogeneity of the repository's environment. However, laboratory observations are necessarily limited to a few months, or perhaps years, and extrapolation to longer periods requires:

- either an understanding of the mechanisms of material degradation over a short period, which it is possible to extrapolate to the long term, on condition that no new phenomenon, latent in the short term, manifests itself over the period;
- or transposition to the conditions of the repository of observations made in more unfavourable conditions, accelerating the speed of the phenomena (this is the case, for example, of iron-clay disturbance, too slow to be observed in the laboratory at the repository temperature, but which is observable at high temperature over short periods). This assumes the availability of experimental data for deducing the kinetics of repository phenomena based on that observed in laboratory conditions;
- or extrapolation of observations made over short periods, under pessimistic environmental conditions, to long periods. This case differs from the previous one in that it is not assumed that there is a transposition law between the experimental observations and the reality in the repository, but we insured by using pessimistic experimental conditions against any possible long-term change in the phenomenon. This is the case, for example, of the "V0.S" model, studying the alteration of glass over short periods under unfavourable conditions (no silica in the external medium, leaching by pure water) to deduce a conservative value from it for the speed of dissolution in repository conditions;
- or by the study of natural cases, as for example for cement-based disturbance or the alteration of bituminous matrices, or archaeological analogues.

Table 5.4 **Some of the main sources of uncertainties in different time frames in the Belgian SAFIR 2 study**

Time frame	Characteristics	Main uncertainties
Thermal phase	Substantially complete containment of spent fuel and vitrified high-level waste in canisters is expected	Lifetime of canisters
		Thermal effects on the clay barrier
		Changes in biosphere
Isolation phase	Stability of the waste forms ensures slow release of most radionuclides; releases are further delayed and attenuated by slow transport through both the engineered barrier system and the geosphere, resulting in insignificant releases from the disposal system into the environment (i.e. containment of the radionuclides within the disposal system)	Evolution of pH in near field
		Early waste matrix corrosion rate
		Evolution of hydraulic and transport parameters within the near field
		Gas generation and transport and the influence of gas on the near field and on the host clay formation
		Changes in the biosphere and aquifers
Geological phase	Dilution, dispersion, diffusion and sorption mitigate releases into the environment (water bearing strata) and into surface waters	Long-term waste matrix corrosion rate
		Transport of retarded radionuclides in host clay formation (exchange with organic matter, co-precipitation)
		Changes in host clay formation
		Changes in the biosphere and aquifers

5.1.4 Time frames in system evolution

An integrated understanding of the events and processes identified as relevant is required in order to assess and communicate how a repository and its geological environment could evolve over time. Some programmes have developed formal methods to address repository evolution over time in as scientific and logical a way as possible.

Dividing time into discrete periods – time frames – in which, for example, particular processes and events affect or dominate system evolution or in which particular safety functions operate can provide the basis of a clear description of system evolution. Defining time frames facilitates the presentation of the safety case, and can also provide a structured framework for modelling system evolution (Section 5.2).

There is no unique way of carrying out this discretisation in time, and different programmes employ different approaches (Appendix 4, observations from responses to Question 2.3). Furthermore, given that a range of continuous processes as well as discrete events can affect the evolution of a disposal system, the division is always to some extent arbitrary.

Time frames can start or end at precisely specified elapsed times – a thousand years, or a million years, say. Alternatively, start and end times can correspond to the system entering or leaving a specified state or situation, i.e. to some shift in how the system performs or provides safety. One boundary between time frames may, for example, correspond to the end of the period of complete containment by canisters, and another to the start of the period subsequent to the onset of glaciation.

The start and end times are then generally left open, reflecting the uncertainty associated with the timing of the key stages in system evolution. A given set of time frames may encompass a range of scenarios – e.g. although there may be different scenarios leading to the breaching of canisters, a time frame of variable duration in which complete containment by canisters is provided could be appropriate to each of these. There may, however, be some scenarios requiring a set of time frames that is different to the one derived for scenarios in which the system evolves broadly as expected, examples being human intrusion scenarios and scenarios in which spent fuel or high-level waste canisters are breached during the period of high heat output.

In the Belgian SAFIR 2 study of spent fuel and vitrified high-level waste disposal, three discrete post-closure time frames were distinguished (Box 5.1). In this somewhat idealised portrayal, the time frames are sequential. The thermal phase comes to an end at the same time as the isolation phase begins, and similarly the end of the isolation phase marks the beginning of the geological phase. In reality there may be overlap between these phases because of the potential for earlier failures of some barriers, and the likelihood that barrier failure will be a long, protracted process and not an event at a specific time. Other subdivisions are possible, although the particular characteristics of the spent fuel and vitrified high-level waste in the thermal phase – not only the high heat output from the waste but also its high radiological toxicity – leads to special emphasis being placed on this phase in many design studies and safety cases.

Box 5.1: **Main post-closure time frames proposed by the Belgian National Organisation for Radioactive Waste and Fissile Materials (ONDRAF/NIRAS) for describing the evolution of a repository for spent fuel/high-level waste in Boom Clay in SAFIR 2**

1. The **thermal phase** of the system: this first phase has been defined as it determines a central design requirement: containment of the high-level waste in an overpack as long as the temperature around the waste is significantly higher than the ambient temperature and as long as an important thermal gradient is present.* As these temperature criteria have not been defined very precisely the thermal period is set as an order of magnitude (1 000 years). So, the rationale for this first time frame is on the functional design level, but stems from the processes that one wants to avoid (high temperature waste matrix dissolution, high temperature radionuclides migration). After a period of 2 000-3 000 years the α-activity in spent fuel is sufficiently low to avoid drastic influence on UO_2 matrix dissolution.
2. The **isolation phase**: the definition of this second phase is based on the expectation that normally no (or almost no) activity will be released from the system (waste, engineered barrier system and host rock) during this period of time. Although radionuclides may or will be leached from the waste matrix after containment failure, the slow releases from the matrix and the slow migration through the engineered and natural barrier (combined with decay) will keep the non-decayed activity within the system for a long time. For the Boom Clay disposal system a "no release from the system" expectation can be argued over a time frame of 10 000 years (order of magnitude).
3. The **geological phase:** activity releases from the system to the biosphere are expected to occur, and doses for an individual from the reference group can be calculated.

* Containment at least during the thermal phase also implies containment over the period of radioactive decay of all the shorter-lived radionuclides ($t_{1/2}$ < 100 years), but this is seen as a consequence, and not as a requirement.

Nirex has proposed dividing its assessment period for low- and intermediate-level waste (nominally 1 million years) into time frames based on the main safety functions, or safety barriers, around which the Nirex repository concept is designed. Four such safety functions have been identified, and four time frames are defined on the basis of these safety functions. Nirex also considers it helpful to include a fifth timeframe, representing the continuing safety provided by the geological barrier even at very distant times, when quantitative assessments may no longer be meaningful. These timeframes are described in Box 5.2. The time frames overlap since the safety functions operate together, rather than sequentially – for example, the geological barrier is present all the time, and the chemical barrier will be operating whilst packages are still intact. They are also nested in that each time frame can be considered to "encompass" all preceding time frames. The duration of the time frames is subject to uncertainty and also variability. For example, some waste containers will remain intact for much longer than others; the chemical and geological barriers will retard some radionuclides for significantly longer periods of time than other radionuclides. Figure 5.1, however, gives a rough indication of the durations of the different time frames for a scenario in which the system evolves as expected.

Box 5.2: **Time frames proposed by Nirex for describing the evolution of a low- and intermediate-level waste repository**

1. Containment

The waste container is mechanically and structurally intact. Only gaseous releases (via container vents) are possible, all other materials are completely contained within the waste packages. Institutional control of the repository site prevents inadvertent human intrusion.

2. The package

The physical containment afforded by the waste packages, including the waste form itself, continues to retard the release of radionuclides by the groundwater pathway, even though localised corrosion may have reduced the integrity of some containers.

3. The chemical barrier

The release of radionuclides continues to be retarded by the reducing, alkaline conditions established in the cementitious repository backfill.

4. The geological barrier

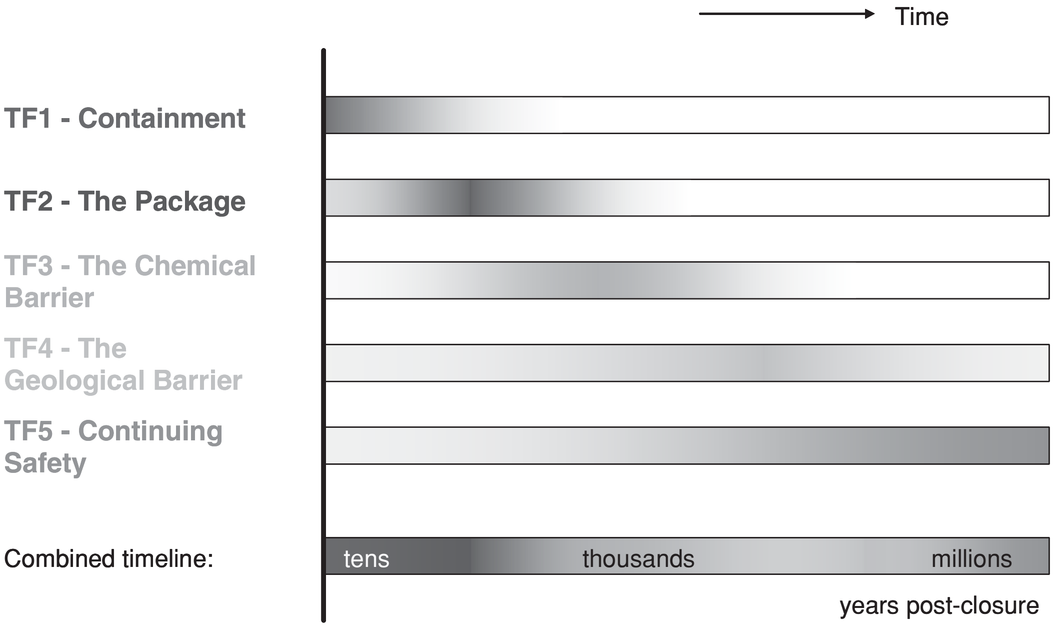
The geological barrier provides a long travel time to the surface, gives substantial dispersion and dilution and retards sorbing radionuclides. This prevents most radionuclides that leave the near field from returning to the surface environment and ensures that any radionuclides that do reach the surface do so in very low concentrations that do not pose any significant health risk.

5. Continuing safety

The long-term stability of the geosphere continues to provide safety at very long times in the future, even under significant external change, which may include major climate change.

In this example, each time frame effectively starts at time "zero". This reflects the fact that all safety functions are present from the start. However, the time frame and the associated safety functions that most appropriately describe the evolution of the repository system changes as time progresses. This can be envisaged as progressively "moving the spotlight" from one time frame to the next as the repository system evolves.

Figure 5.1: **Illustration of the relative timescales of the five time frames considered by Nirex (a version of this figure was presented by Nirex at 7th IGSC meeting, 12-14 October 2005)**



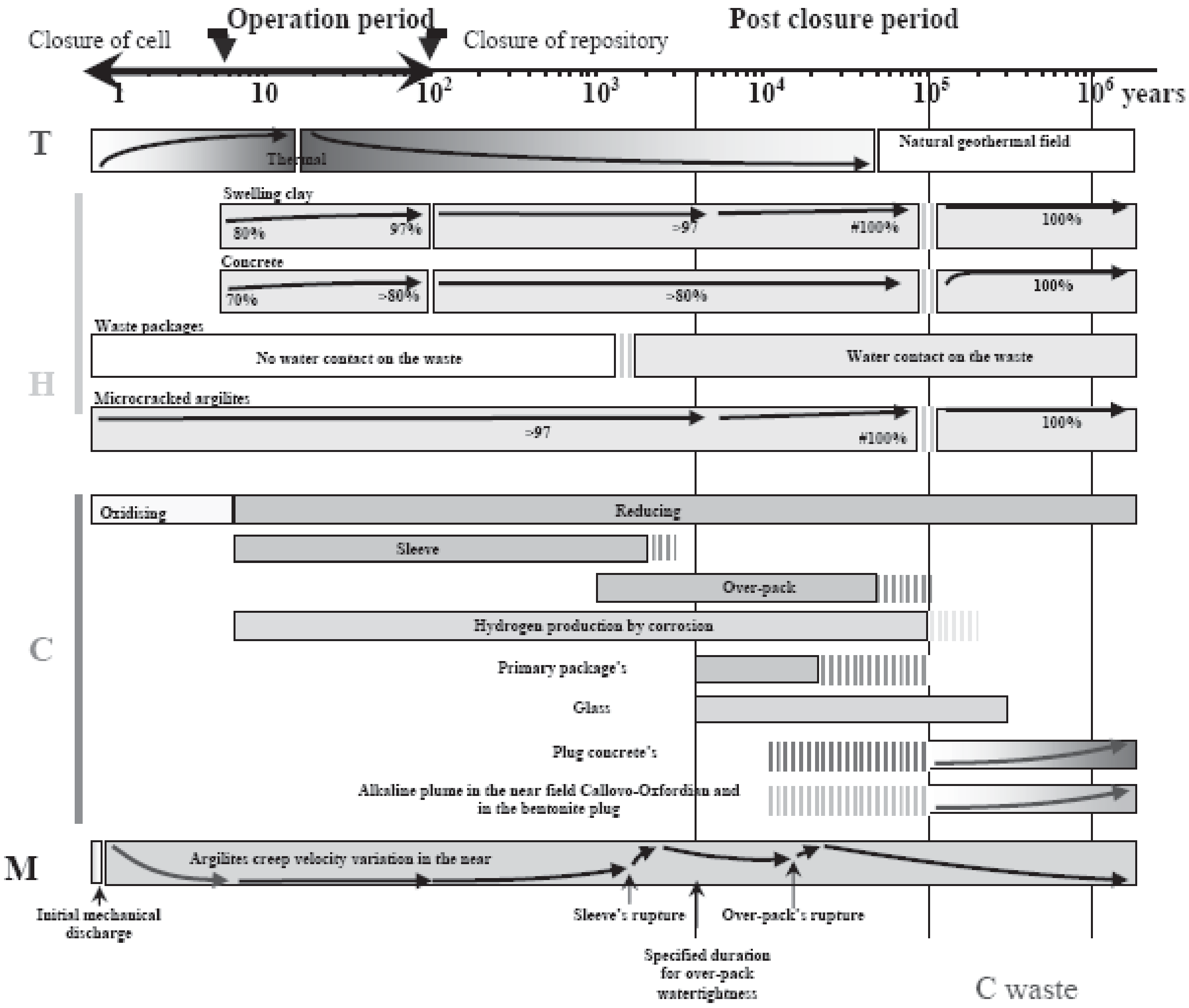
In the approach developed in France by Andra, termed Phenomenological Assessment of Repository Situations (PARS), a series of time frames and repository situations is identified, dividing repository evolution into intervals in space and time on the basis of the phenomena that may occur and the associated uncertainties in each time frame and situation. The discretisation scheme is based on expert judgement as informed by evidence from laboratory and underground rock laboratory (URL) experiments, natural analogues, scoping calculations, modelling studies and performance assessments.

In Dossier 2005 Argile (Andra, 2005a-c), PARS was applied to each component of the repository (engineered components and geological environment) from the operating phase up to a million years, leading to a description of:

> *"the (most) probable (expected) phenomenological evolution of the deep geological disposal and its geological environment over time according to the scientific knowledge/understanding and the conceptual design, including simplification based on importance assessment of the phenomena as much as reasonable."*

Figure 5.2 from Dossier 2005 Argile illustrates the timescales of the major thermal, hydraulic, mechanical and chemical (THMC) processes that are expected to occur in the engineered barrier system for vitrified high-level waste (with uncertainty in these time frames, indicated by dashed bars).

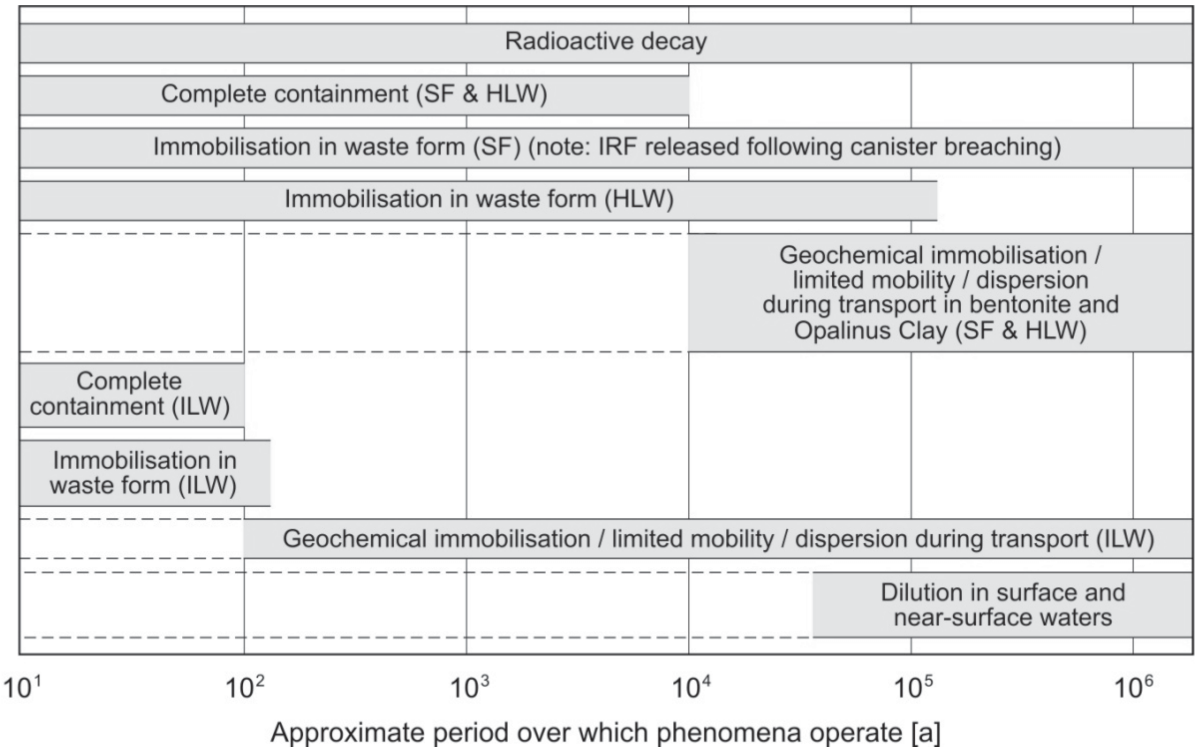
Figure 5-2: **Illustration of the time frames characterising the evolution of the engineered barrier system for vitrified high-level waste (figure presented by Andra at 7th IGSC meeting, 12-14 October 2005). T: thermal, H: hydraulic, C: chemical, M: mechanical processes. Dashed lines represent uncertainties. Arrows indicate the variation of intensity of a process with time. Percentages refer to the degree of saturation.**



As a final example, Figure 5.3 shows the time frames over which some key phenomena contribute positively to long-term safety in the Swiss concept for the disposal of various categories of long-lived waste.

The use of time frames in developing and communicating a safety case – whether it is done and how it is done – is generally a decision of the implementer. Regulations do, however, in some cases, set out a series of time frames for which requirements on safety assessment vary in a stepwise manner over time, as described in Section 3.3, reflecting the increasing uncertainties in the evolution of a disposal system and the assessment of its performance.

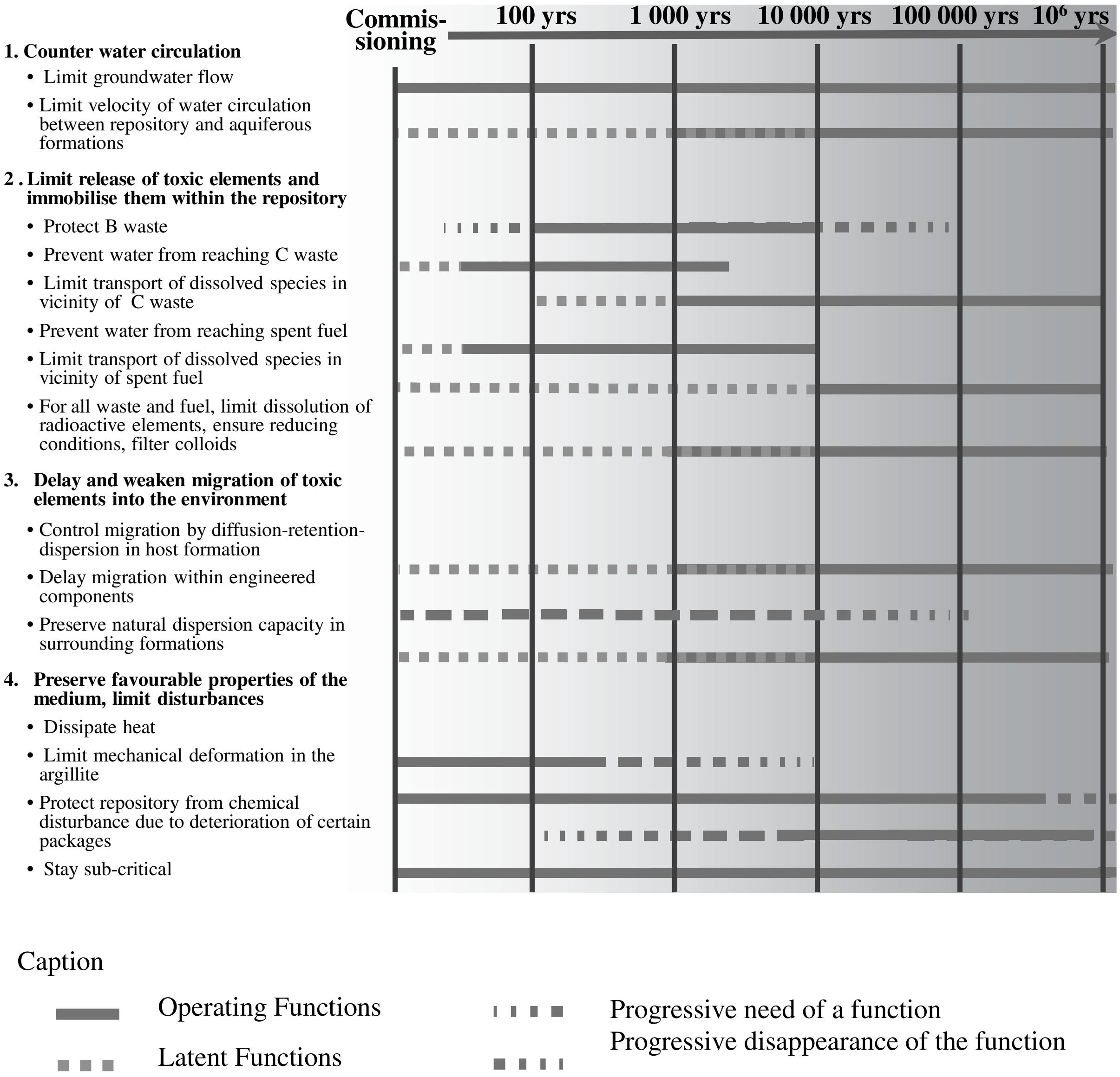
Figure 5-3: **Some key phenomena contributing positively to long-term safety and the time frames over which they are expected to operate in the Swiss concept for long-lived waste disposal in Opalinus Clay – (figure presented by Nagra at 7th IGSC meeting, 12-14 October 2005)**



5.1.5 Evolution of safety functions

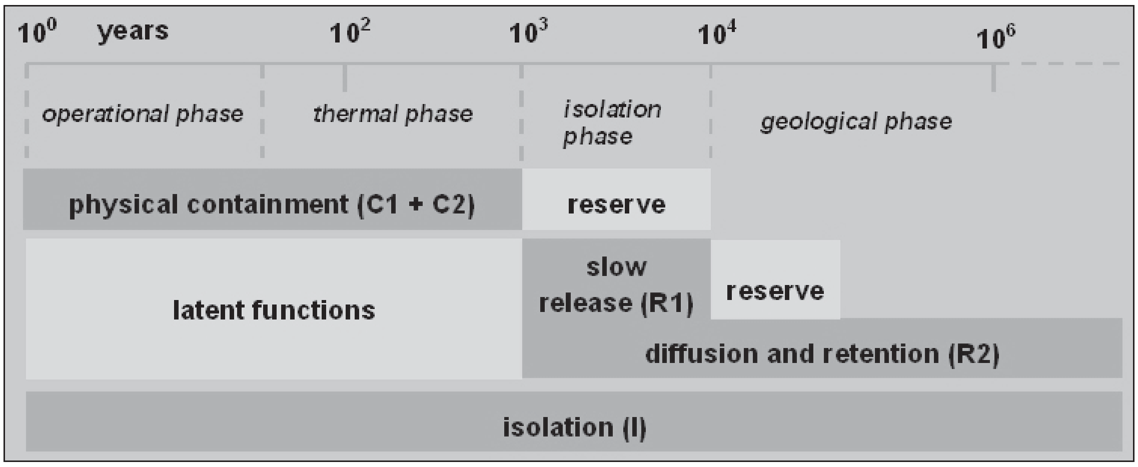
The emerging preference for expressing how a repository provides safety as a function of time in terms of the evolving safety functions was already noted in Section 3.1.3. Figure 5.1 gives one example of this. As a further example, Figure 5.4, which is from Dossier 2005 Argile, shows the main safety functions in the French concept for long-lived waste disposal in argillaceous sediment broken down into a number of sub-functions that represent requirements on repository siting and design. Each sub-function is characterised by a required performance level, a period during which the function has to be provided by the system, and the system components (one or more) that have to fulfil the function. The duration that the sub-function has to be available is based mainly on the phenomenological analysis of the repository evolution (Section 5.1.4). A final example is given in Figure 5.5, which shows the safety functions provided as a function of time in the Belgian concept for high-level waste and spent fuel disposal.

Figure 5.4: **Safety functions and the time frames over which they are expected to operate in the French concept for long-lived waste disposal in argillaceous sediment — latent functions shown in green (figure presented by Andra at 7th IGSC meeting, 12-14 October 2005)**



Note: **C waste is vitrified high-level waste. B waste includes various categories of waste from spent fuel reprocessing.**

Figure 5.5: **The safety functions and time frames identified in the Belgian disposal programme for spent fuel and vitrified high-level waste disposal in a plastic argillaceous formation (the Boom Clay) and the time frames over which they are expected to operate (from Figure 2 of de Preter *et al.* 2005)**



Key to symbols

The *physical containment* function *(C)* is divided into two sub-functions:

1. The *watertightness* sub-function *(C1)* is associated with the engineered barrier system and, in particular, the overpack. The purpose of this sub-function is to prevent water coming into contact with the waste form.
2. The *limiting the water inflow* sub-function *(C2)* is mainly associated with the natural geological barrier, but also with those parts of the engineered barrier system capable of absorbing water. This sub-function delays the time at which infiltrating water interacts with the watertight barriers and with the waste form, and limits the quantity of infiltrating water.

The *delaying and spreading the releases* function *(R)* is also divided into two sub-functions:

1. The *slow release* sub-function *(R1)* delays the release of radionuclides by the waste matrix, and by the waste container and overpack.
2. The *diffusion and retention* sub-function *(R2)* delays the transport of radionuclides through the engineered barrier system and the Boom Clay.

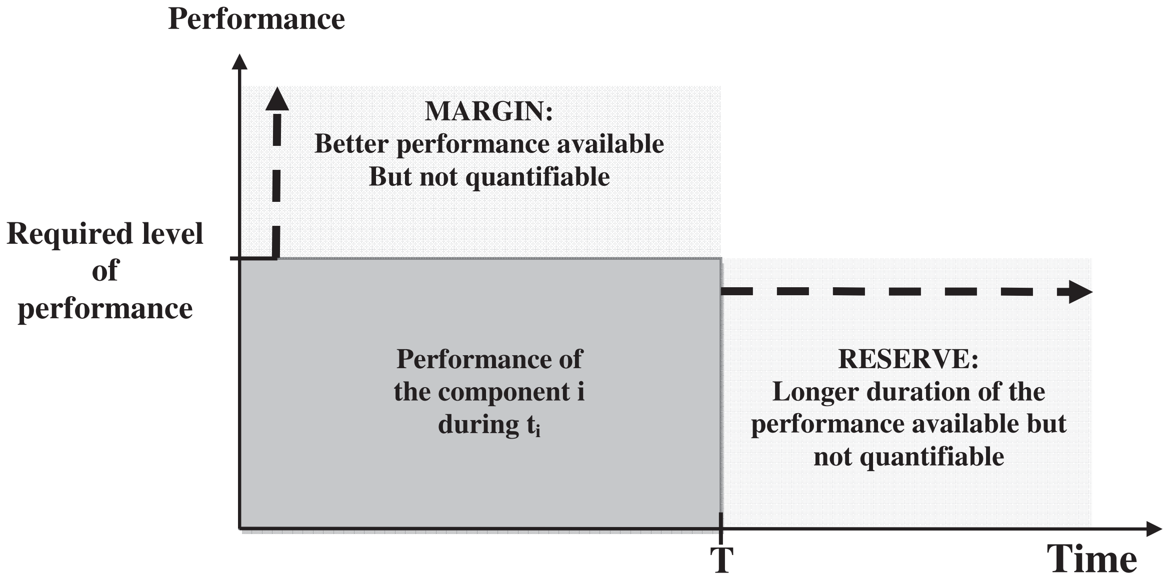
The *isolation* function *(I)* refers to the limitation of the possibilities for human intrusion and protection against surface events and processes.

Some safety functions, sometimes termed **effective functions**, are confidently expected to operate in a given time frame (e.g. those shown in dark orange in Figure 5.5 and by continuous lines in Figure 5.4). They may, however, be complemented by additional safety functions (shown in light orange in Figure 5.5 and by broken lines in Figure 5.4) that provide additional qualitative arguments that should favour overall confidence in safety, even though they may not be included in safety assessment calculations for a given time frame.

These are:

Reserve functions – which are safety functions that may well contribute positively to system performance, but uncertainties are such that they cannot be relied upon with confidence to provide the required levels of performance throughout the full time frame that it could, in principle, operate. The concept is illustrated in Figure 5.6, which shows how, at a time *T*, a function can go from being effective to reserve when the level of performance required for it to be classified as effective can no longer be assured (quantified). Containment by canisters, for example, becomes a reserve function at times when there is some evidence that containment will continue, but the evidence is judged to be insufficiently sound to take credit for containment at these times in assessment calculations. Monitoring and control may become reserve functions (or sub-functions contributing to the higher-level function of isolation) at times beyond a few hundred years (Section 4.2). This is because, in reality, future generations may choose to continue these measures, which will then contribute to the function of isolation, but, at the present time, there is no way of knowing that this will in fact be the case. The existence of reserve functions provides qualitative support for a safety case that complements conservative safety assessment calculations based on effective functions.[1] Figure 5.6 also shows that, in a time frame when a function can be relied upon with confidence to provide the required levels of performance, a still higher level of performance may be achieved in reality, even though no credit is taken for this in safety assessment because of uncertainties (the concept of "margins"). Some reserve safety functions may be reclassified effective functions (or the time frame in which they are classed as effective extended) at a later stage in the development of a safety case if better understanding leads to reduced uncertainties.

Figure 5.6: **Illustration of the concepts of reserve functions and margins (figure presented by Andra at 7th IGSC meeting, 12-14 October 2005)**



Latent functions – which are safety functions that operate within a given time frame only if other safety functions (unexpectedly) fail to operate. Figure 5.4 shows the example of the delaying and spreading of releases (e.g. by geosphere transport) as a latent function during the period of complete

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[1] A realistic rather than a conservative approach is of more use for safety assessments aimed, say, at design optimisation – see Section 5.2 for a discussion of the limitations of a conservative approach.

physical containment by the engineered barriers in the case of the Belgian concept. In this concept, the physical containment period extends to at least a thousand years (although it is a reserve function for up to 10 thousand years). Similar latent functions are also present during complete containment in concepts for spent fuel and vitrified high-level waste disposal where still longer periods of containment by canisters are expected. Box 5.3 gives examples of latent functions in the case of the KBS-3 repository system developed by the Swedish and Finnish programmes, where canisters are expected to provide containment of radionuclides for at least a million years.

Box 5.3: **Latent functions in the Swedish/Finnish KBS-3 concept that provide continued safety should canister failure occur**

- If the canister failure is of limited extent, e.g. a pinhole caused by corrosion, the failed canister can continue to provide isolation for the tens to hundreds of thousands of years.
- The limited degradation rate of the ceramic waste form provides a substantial limitation of radionuclide releases in case of a canister failure.
- The buffer is expected to retard most radionuclides substantially over the entire assessment period for expected conditions.
- The geosphere is also expected to retard most radionuclides substantially over the entire assessment period. There are however large differences between deposition holes due to the natural variability of the host rock hydraulic and transport properties.

5.2 Safety assessment modelling

5.2.1 The evolving spatial scales address by modelling

Quantitative safety assessment modelling tends to focus on potential radionuclide releases from a repository to the biosphere. Such modelling typically varies as a function of time in the spatial scale that it addresses. In general, radionuclides are confined within waste containers or canisters for an initial period. At later times, releases may occur, but be confined within the engineered barrier system. At still later times, releases may occur from the engineered barrier system, but be confined within a limited part of the geological environment around the repository. Eventually, some releases may reach the surface environment. The thermal and chemical effects of the repository also extend over increasing distances as a function of time. Thus, different spatial scales may be appropriate to consider when modelling different time frames.

As an example, in the time frames considered by Nirex (Figure 5.1), modelling addresses different and nested spatial scales, namely:

Time frame 1: A single waste container (package-scale);

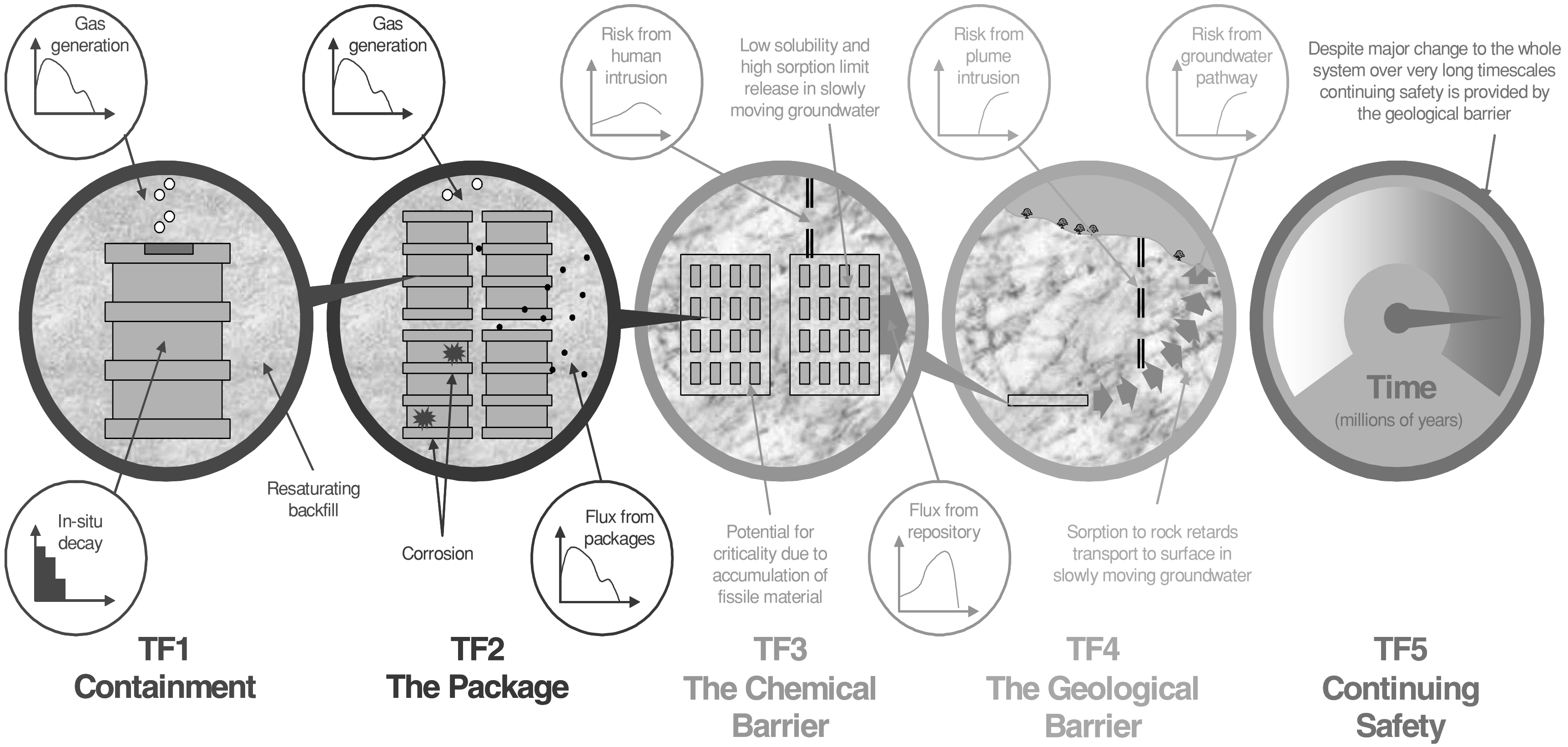
Time frame 2: An array of waste packages (repository vault-scale);

Time frame 3: The repository engineered barrier system (repository-scale); and

Time frames 4 and 5: The surrounding geosphere (regional-scale, maybe a few kilometres).

This is illustrated in Figure 5.7, which also shows that the main modelling output (or performance indicator) can vary according to the time frame and spatial scale under consideration.

Figure 5.7: **Schematic illustration of the boundaries of the five time frames proposed by Nirex with key performance measures highlighted (a version of this figure was presented by Nirex at 7th IGSC meeting, 12-14 October. 2005 – same colour scheme as Fig. 5.1)**



As a further example, in the PARS methodology developed by Andra in which repository evolution is described in terms of "situations" (Section 5.1.4), each situation is analysed using a model appropriate to the phenomena and the spatial and temporal scales of concern. The models are linked to take account of conservation laws and the coupling between thermal, hydraulic, mechanical, chemical and radiological processes.

5.2.2 Treatment of uncertainty

Firm predictions of repository evolution and performance over long timescales are neither possible, nor are they a regulatory requirement in any country (Section 3.3). How to deal with generally increasing uncertainties in repository evolution and performance is, however, a key problem to be addressed in carrying out safety assessment modelling in support of a safety case.

Many uncertainties in the evaluation of releases from the geosphere to the biosphere can be quantified or bounded and dealt with in safety assessment using, for example, conservative model simplifications, conservative data or evaluating multiple cases spanning the ranges of uncertainty. However, especially where biosphere modelling is required in order to express the consequence of calculated releases in terms of dose or risk, or in terms of certain alternative safety indicators such as concentrations in surface or near-surface aquifers (where the dilution potential of the biosphere is relevant), there are large and sometimes unquantifiable uncertainties that cannot be treated in this way. Rather, they are typically dealt with by adopting a "stylised approach", or avoided, to some extent, by using complementary safety indicators that do not require assumptions to be made regarding the future state of the biosphere. Model simplification and stylisation are discussed in detail in Section 5.2.3. Complementary safety indicators are discussed in Section 5.2.4.

5.2.3 Model simplification and stylisation as a function of time

Safety assessment modelling inevitably involves a degree of simplification because of the complexity of the systems considered, the impossibility of comprehensive and complete characterisation and the limited understanding that is available for some transient processes. Simplifying assumptions can also be used to avoid treating some poorly defined uncertainties explicitly.[2] Such assumptions – which can include the exclusion from models of some poorly-understood features, events or processes – are typically argued on the basis of supporting calculations or qualitative arguments either (i) to have negligible impact on performance, or (ii) to be conservative. Alternatively, simplifying assumptions may be "stylised" (see below).

Models should represent relevant features, events and processes in each time frame in an appropriate degree of detail (Appendix 4, observations from responses to Question 7.1) There is a tendency for models to be more realistic at early times (possibly with explicit treatment of early transient processes directly important for the safety functions), with increasing simplification and stylisation at later times. This tendency is partly due to generally increasing uncertainties. In addition, however, as the overall spatial scales addressed by modelling generally increase with time, it may be adequate to treat some features and processes characterised by much smaller spatial scales by averaging over spatial variability. Thus, in the example in Figure 5.1, it may be most appropriate to

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[2] Better defined uncertainties are typically treated in safety assessments using models and databases to evaluate different possibilities for the evolution and performance of a disposal system that fall within identified ranges of uncertainty.

model individual waste packages explicitly in time frames 1 and 2, but to incorporate their properties into average properties of the repository vaults in later time frames.

Box 5.4: **Stylisation**

NEA documents on important aspects of safety cases provide the following definitions for stylised models or scenarios:

- "A stylised presentation refers to a situation where a part of the disposal system is treated in performance assessment in a standardised or simplified way. The need for stylised presentations occurs if there is a general lack of experimental evidence such that decisions on treatment and parameters values put into performance assessment is highly judgmental." (NEA, 1997)
- "Stylised approaches are typically used for situations where there is inherent and irreducible uncertainty, to illustrate system performance and to aid communication. (NEA, 2000(

The NEA Report on "Scenario Development Methods and Practices" (NEA, 2001) observed that "[i]n PA, some FEPs and issues (e.g. human intrusion into a deep repository, and some aspects of the biosphere) can only be treated by means of stylised scenarios."

It should also be noted that, to some extent, some aspects of the systems may in reality become simpler over time as, for example, the early thermal, hydrogeological, mechanical, chemical and biological perturbations evolve to states approaching equilibrium. The increasing simplification and stylisation of assessment models with time as a result of increasing uncertainty is also reflected in some national regulations, although this varies from country to country. It is, however, generally considered a matter for the implementer to justify which events and processes to include in assessment models within each of the time frames and how much realism is required in modelling different scenarios over different time frames.

Simplified assessment modelling is often complemented and supported by more realistic "process modelling" that aims at a representation of a limited part of the system, or of events occurring externally to the system, that is as realistic and detailed as possible (Appendix 4, observations from responses to Question 7.3). Such models provide input to assessment models, for example bounding the range of future climate states that may need to be considered and the time frames over which they may occur. Process models may explicitly consider transient evolution. Hydrogeological and hydrogeochemical modelling may, for example, evaluate the change in flow conditions and groundwater composition over time. Assessment models, on the other hand, often assume steady state flow conditions and groundwater compositions at all times, but are applied in safety assessment in a series of runs evaluating a wide range of possibilities for these conditions. This treatment of variability with time as a time-independent parameter uncertainty is under discussion, for example in the United Kingdom, and the development of a more realistic treatment of time dependency is seen as a potential area for future model enhancement.

Stylised modelling is widely considered appropriate for the biosphere, climate change and human intrusion at times when uncertainties cannot readily be quantified or bounded, or when the probability of some "initiating event" can be estimated, but the timing is unknown. In addition, certain more speculative or poorly researched features and events, such as repository seal failures, canister defects, the occurrence of undetected geological features and the occurrence of natural events beyond the period of geological stability, are sometimes treated in scoping calculations in a stylised manner (Appendix 4, observations from responses to Question 7.4). In stylised modelling, certain assumptions are assumed to hold, even though they cannot be shown necessarily to hold based on current scientific understanding. Such assumptions are to some extent arbitrary although they should be *constrained* by scientific understanding, and, while often pessimistic, they are not necessarily the most conservative assumptions possible. They are also generally required to be mutually consistent. The regulator may take upon itself the responsibility of defining stylised assumptions, which the implementer can then adopt without further justification in safety assessment. Alternatively, the definition of such stylised assumptions may be seen as the responsibility of the implementer, but regulations may acknowledge that the approach is acceptable.

Stylised modelling of the biosphere

In the case of biosphere modelling, a stylised approach is generally used for the entire post-closure period. Biosphere modelling requires knowledge or assumptions regarding, for example:

- the evolution of dilution in surface waters and near-surface aquifers, and
- the evolution of aspects of human lifestyle that could affect exposure pathways.

These evolutions are dependent on factors such as the nature of future human societies, human behaviours, and energy and food sources, all of which become highly uncertain or speculative over short timescales (a few decades, say) – certainly timescales that are much shorter than those associated with, for example, radionuclide release and transport. Furthermore, many of these uncertainties are not amenable to reduction by site characterisation, surveys of human behaviour, or research into future climates.

In view of these uncertainties, there is a consensus that it is appropriate to carry out biosphere modelling on the basis of “stylised biospheres”, i.e. representations of the biosphere based on stylised assumptions that are acknowledged to be simplified and not necessarily realistic, but are internationally agreed and accepted as valid for modelling studies (e.g. IAEA, 1999; NEA, 1999c). These scenarios should be viewed as illustrative; they are developed and can be bounded in order to allow for an assessment of potential performance without giving rise to endless speculation about evolutions of future society, technology, etc. Often, the use of stylised assumptions for the biosphere provide for a calculation that gives perspective for what the dose might be if the releases were to occur today – which is considered useful information for both stakeholders and decision makers.

A stylised approach to biosphere modelling is all the more justified because biosphere assessment is undertaken only for the purpose of interpreting radionuclide releases in terms of indicators, particularly dose and risk, that are used to test the capability of the system to provide adequate isolation of the waste and containment of radionuclides (see e.g. ICRP, 2000). Unlike the repository and its geological environment, the biosphere is not regarded as being a part of a geological disposal system, and is not considered to have any protective or safety function. It must always be emphasised in a safety case that the results provided are indications or illustrations of the potential levels of protection that a repository provides.

In terms of regulatory guidance, Swedish regulations, for example, indicate that, in the first thousand years post-closure, it is reasonable to base risk calculations on the biosphere as it is observed at a site today. In the longer term, however, risk calculations should be based on illustrative scenarios for biosphere evolution.

Stylised modelling of climate change

While some variations in climate are possible over a 1 000 to 10 000 year time frame, more significant changes are likely beyond about 10 000 years due to glacial cycling. The nature and extent of any future climate change that could affect deep groundwater movement and chemical composition over this longer time frame is largely uncertain. On the basis of scientific understanding of the impact, for example, of increased precipitation rates, permafrost development and glaciation on conditions within and around a repository, prognoses can be made of how a repository and its geological environment would evolve and perform under various climate change scenarios (in some but not all systems, it may be argued that groundwater movement and chemical composition at repository depth is largely decoupled from climate change – see, for example, Section 4.3.6.6 in Nagra, 1994). The scenarios themselves, however, are generally stylised, though constrained by climate models, and may be defined either by the implementer or regulator. Stylisation has to date involved modelling a sequence of rapid transitions between future climate states using climate cycles based on past climate data, but without inclusion of uncertainty in the timing of climate changes (Appendix 4, observations from responses to Question 7.4).

Climate change will also have a significant impact on the characteristics of the biosphere and on human lifestyles, and hence on any actual doses received.[3] The correlation between the impact of climate change on the repository and its geological environment, on the biosphere, and on human lifestyles is not, however, uniformly addressed in either regulation or safety assessment. In some cases, the stylised assumption is made that the future biosphere and future lifestyles can be decoupled, consistent with the approach of separating the assessment of the biosphere from that of the repository and its geological environment mentioned above. This decoupling is acknowledged to be unrealistic, but requiring an implementer to project future human lifestyles and activities for given changes in climate, or even without changes in climate, is even more unrealistic. There are, however, other feasible alternative solutions, such as a stylised biosphere and lifestyle evolution, with lifestyles modelled, at any given time, after contemporary communities that live in relevant climatic conditions, and adjusted if necessary to be even more compatible with the proposed climate states.

Stylised modelling of human intrusion

It is generally considered that the nature and extent of any future human intrusion cannot be judged on a purely scientific basis. It is, however, possible to specify a number of human intrusion scenarios based on present day technologies and human habits that can be used to illustrate the consequences of intrusion under a given set of stylised assumptions. Site- or concept-specific factors should constrain the intrusion scenarios to be considered and their probabilities. At the site of the Waste Isolation Pilot Plant (WIPP) in the US, for example, which has been exploited in the past for mineral resources, an indication of the likely rate of future drilling can be obtained from records of past drilling, and this rate was assumed in the stylised human intrusion scenario defined by the regulator (Helton & Marietta, 2000). Even if site-specific information on drilling rates and techniques are not available, there is still a need to define the possible types of intrusion, their frequency, their location relative to the waste, etc., and in this need is often fulfilled by using stylised scenarios. (See U.S. regulations for Yucca Mountain, for example, at 40 CFR 197.)

Some safety assessments exclude the possibility of human intrusion in a safety assessment over an early time frame of a few hundred years[4] on the grounds that it will be prevented or at least made highly unlikely by, for example, post-closure controls, record-keeping and surface markers, which are thus considered to provide a safety function in this time frame (Chapter 4). The possibility of human

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[3] Even at earlier times (a few hundred year post closure), safety assessment does not evaluate actual doses, but rather a potential dose based in part on stylised assumptions.

[4] 100-500 years was a time frame for the exclusion of human intrusion given in many of the questionnaire responses.

intrusion must be considered at any time after passive institutional control can no longer be assumed, generally with a time-independent probability (Appendix 4, observations from responses to Question 6.2c). In the specific case of direct penetration of a metal canister using present-day technology, this may require weakening of the canister by corrosion before a driller would be unaware that penetration has occurred, and, if so, can be excluded for a longer period. On the other hand, the potential radiological consequences of human intrusion, either to the intruder or to public as a result of damage to the repository, tend to decrease with time on account of the decay of the radioactivity of the waste (although the consequences to the intruder may remain significant for much longer – see, for example, Figure 2.2). Often, therefore, the stylised and conservative assumption is made that intrusion occurs immediately upon the lapse of such controls.

5.2.4 Indicators evaluated by safety assessment modelling in different time frames

Some programmes evaluate (stylised) dose and risk as safety indicators for as long as meaningful statements can be made regarding the broad evolution of a disposal system. This is sometimes a requirement of regulations (Section 3.3). Others take the view that these indicators have little or no meaning in time frames when significant changes in the surface environment, in particular as a result of major climate change, cannot be excluded (Appendix 4, observations from responses to Question 9.1a). There is a trend in some recent safety cases towards evaluating, in addition to dose and risk, additional safety indicators that can provide complementary evidence and arguments for safety. These include, for example, radiotoxicity fluxes from the geosphere and concentrations in the biosphere due to radionuclides released from the repository (e.g. Andra, 2005a-c; JNC, 2000; Nagra, 2002; ONDRAF/NIRAS, 2001).

Such complementary indicators can avoid to some extent the difficulties faced in evaluating and interpreting doses and risks, and their use can be seen as complementary to the stylised biosphere modelling described above. They may be increasingly emphasised or even substitute for the evaluation of dose and risk at later times as the assumptions underlying dose and risk calculations become more difficult to support. As described in Section 3.3, the use of complementary safety indicators is sometimes the result of regulatory requirements. Furthermore, even if regulatory criteria relate only to dose or risk, the implementer may still choose also to evaluate other safety indicators in order to provide complementary evidence in support of a safety case that may be of interest, for example to other stakeholders.

The safety indicators that are most often considered address the consequences of releases from the repository. The safety of a geological repository is, however, dependent on its capacity not only to contain radioactivity (and any chemically toxic components), but also to isolate the waste from the environment normally accessible to humans. Thus, indicators such as those shown below in Table 5.5 should be viewed only as partial indicators of safety, and must be complemented by considerations of, for example, the likelihood and consequences of human intrusion, and long-term geological processes such as uplift and erosion that have the potential to lead to eventual exposure of the waste at the surface.

The use of complementary safety indicators has been widely discussed in international fora under the auspices of the IAEA (IAEA, 1994, 2003), and in more detail in the European Commission Research Project on Testing of Safety and Performance Indicators (SPIN) (Becker *et al.,* 2002), which has provided observations on and recommendations for the use of different safety indicators in different time frames that are increasingly reflected in current practice in many programmes. Table 5.5 gives an overview of the results of the assessment of various safety indicators from SPIN, showing in particular indicators that replace the need for the evaluation of biosphere pathways and dilution in aquifers.

Table 5.5: **Overview of the results from SPIN of the assessment of safety indicators (from Table 9.2 of Becker *et al.,* 2002)**

Indicator	Measure for system safety	Reference values		Weighting scheme		Calculable by use of PA models	Easy to understand	Added value	Biosphere pathways excluded	Dilution in aquifer excluded
		available	safety-relevant	available	safety-relevant					
Effective dose rate	+	+	+	+	+	+	+	+	-	-
Radiotoxicity concentration in biosphere water	+	+	+	+	+	+	+	+	+	-
Radiotoxicity flux from geosphere	+	+	+	+	+	+	+	+	+	+
Time-integrated radiotoxicity flux from geosphere	+	+	-	+	+	+	-		+	+
Radiotoxicity outside geosphere	+	+	-	+	+	+	-		+	+
Relative activity concentration in biosphere water	+	-		-		+	+		+	-
Relative activity flux from geosphere	+	-		-		+	+		+	+

The individual or effective dose rate (i.e. the effective dose to a representative human individual in a year) is calculated by the consideration of relevant exposure pathways. Assumptions about the biosphere, including locations and lifestyles of future generations, are necessary to calculate, for example, quantities of activity ingested or inhaled, and dose coefficients are needed to convert to these quantities to dose. Many of these assumptions become highly speculative over time. Indicators that are evaluated without the need for such assumptions can be seen as having advantages in the longer term. Some other indicators require assumptions to be made about aquifer dilution. Aquifer dilution is also considered to become highly uncertain, but over a longer time frame. Thus, indicators that circumvent the need to evaluate both biosphere pathways and aquifer dilution may have advantages in the still longer term. Similarly, indicators that circumvent the need to evaluate biosphere pathways, aquifer dilution and dose coefficients may have advantages in the very longest term.

In the recommendations of SPIN, preferred application time frames for three proposed safety indicators are given, although it is also noted that each indicator can be applied in all time frames:

- effective dose rate, which requires a representation of biosphere pathways and is most relevant at early times (the first several thousand years);
- radionuclide concentration in biosphere water, which requires a representation of dilution in aquifers and surface waters and is preferred for medium time frames (from several thousands of years to several tens of thousands of years);
- radiotoxicity flux from the geosphere, which requires neither of the above and is preferred for later time frames (hundreds of thousands of years or more).

It does not follow from a shift of emphasis away from dose and risk and towards other indicators at later times that different levels of protection are necessarily acceptable or expected.

Rather, as discussed in the context of regulatory requirements in Section 3.3, it is an acknowledgement of the limitations of what is possible in, and what is reasonable to expect from, safety assessment modelling. Safety criteria take the form of comparisons of the calculated values of the indicators with reference values. Naturally occurring concentrations and fluxes can provide the basis for reference values for activity (or radiotoxicity) concentrations in biosphere water and fluxes from the geosphere (IAEA, 2005). For example, activity fluxes can be compared to fluxes in biosphere aquifers and rivers close to a repository site, the rate of release of activity due to the erosion of the reference biosphere area, and the rate of ingestion of activity by consumption of mineral water (Appendix 4, observations from responses to Question 9.1b). The objective of such comparisons is generally to test whether repository-derived concentrations and fluxes represent a significant perturbation to naturally occurring concentrations and fluxes (bearing in mind that the latter may vary in both time and space). Such comparisons, however, need to be used with caution. This is because, for example, the isotopic compositions of natural systems will differ from those of repository releases, and the assumption should not be made that natural situations are necessarily harmless. Reference values for complementary safety indicators are generally left for the implementer to determine and justify, the exception being Finnish regulations, where geo-bio flux constraints are specified in regulations (Section 3.3).

5.2.5 The overall time frames covered by safety assessment modelling

In countries where regulations do not explicitly specify the time frames over which protection needs to be considered (Sections 3.3.3 and 3.3.4), the implementer has the challenge deciding on the level and style of assessment to be carried out over different time frames, which will then be subject to review by the regulator.

It can be helpful to differentiate between the period addressed by the safety case, in which a range of quantitative and more qualitative arguments is presented, and the possibly more limited period over which safety assessment modelling is carried out – i.e. quantitative modelling of the magnitude and consequences of potential radionuclide releases.

The period addressed by safety assessment modelling cannot, for practical reasons, extend indefinitely into the future. The factors considered in determining the overall time frame covered by safety assessment modelling and their weighting can vary considerably between different national regulations and between safety assessments, many being programme and concept specific (see Appendix 4, responses to Question 2.2 for examples). Modelling time frames may either be prescribed in regulations or left to the implementer to determine and justify. The time frames covered by modelling in recent safety assessments range from 10 000 years to one hundred million years (Table 5.6), although a million years seems to be emerging as a commonly accepted time frame in recent safety assessments (Appendix 4, observations from responses to Question 2.2).

Truncating calculations too early may run the risk losing information – for example on the possible timing and magnitude of peak consequences – that could, for example, guide possible improvements in system design and thus strengthen the safety case. At sufficiently distant times, however, uncertainties call into question most of the assumptions made in evaluating radionuclide releases. The time frame over which a model is valid or applicable is usually not clear-cut, and estimating this time frame generally involves expert judgement.[5] Safety assessment modelling is sometimes extended to times when fundamental underlying assumptions, including that of geological

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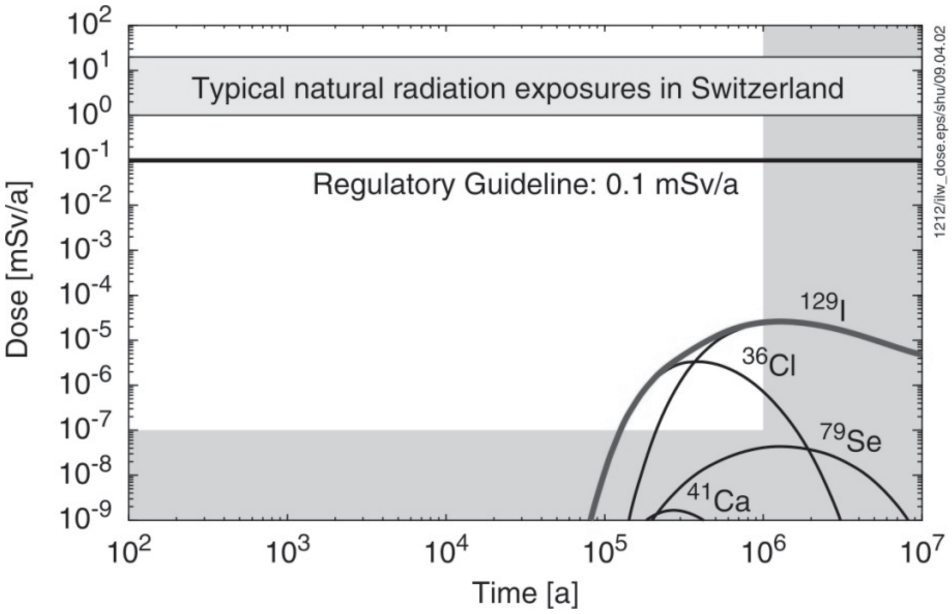
[5] No national regulations explicitly allow a relaxation on the validation requirements for models and databases with increasing time, although guidance from some regulations indicate there is a natural diminishment in the degree of credibility that can be attached to numerical results over very long times.

stability, are certainly no longer well supported by scientific understanding. To avoid undermining confidence in a safety case, qualifying statements regarding the scientific reliability of the models must accompany the presentation of the results, so that they may be properly interpreted. It must be emphasised that the results are tentative and address questions such as:

> "*what if the assumptions underlying the models and data, that are well supported (at least in terms of their conservatism) up to a certain time, were to hold for still longer times?*"

In Figure 5.8, for example, which is taken from the Swiss Project Opalinus Clay (Nagra, 2002), the shaded area beyond one million years indicates that calculated releases should be viewed cautiously since they rely on more speculative information and may have little meaning in terms of actual risks; i.e. they are based on near field and geosphere model assumptions that are not necessarily well supported, since, in particular, significant geological changes cannot be ruled out in this time frame. The results are nevertheless presented since they provide information on the evolution of the calculated doses for the model system (rather than for the actual system).

Figure 5.8: **Example of the presentation of evaluated dose as a function of time. Shaded areas indicate Swiss criteria for results that should be viewed with particular caution: calculated doses beyond a million years are based on model assumptions for releases to the biosphere that are not necessarily well supported, and also evaluated doses below 10^{-7} mSv per year are judged to be so low that – if interpreted as actual doses – they would have no radiological meaning (figure presented by Nagra at 7th IGSC meeting, 12-14 October 2005)**



Note: Evaluated doses due to spent fuel in the Reference Case of Project Opalinus Clay (Nagra, 2002).

Table 5.6: **Some examples of the time frames covered by modelling in recent safety assessments**

Assessment	Time frame covered by assessment modelling	Determined by regulation
Project Opalinus Clay (Nagra, 2002)	10^7 years (but with the period beyond a million years assigned a different status, as discussed in Nagra 2002 and in the present document below)	No
Nirex GPA (Nirex, 2003)	10^6 years (an appendix of Nirex 2003 is devoted to justifying the assessment time period)	No
H12 (JNC, 2000)	10^8 years	No
SAFIR 2 (ONDRAF/NIRAS, 2001)	10^8 years (but the highly illustrative nature of the calculations beyond 10^5 years was mentioned)	No
"Dossier 2001 Argile" (Andra, 2001) and "Dossier 2005 Argile" (Andra, 2005a-c)	10^6 years	No
SITE-94 (SKI, 1996)	10^6 years	No
SR-97 (SKB, 1999)	10^6 years	No
SR-Can (SKB, 2004)	10^6 years	Yes
Final Environmental Impact Statement (US DOE, 2002a) Site Suitability Evaluation (US DOE, 2002b)	10^6 years 10^4 years for the compliance period	Yes (regulations now under revision by U.S. EPA – see Appendix 2)

Other factors besides increasing uncertainty that may be taken into account when deciding at what time to truncate safety assessment model calculations are elaborated in Box 5.4, and include (Appendix 4, observations from responses to Question 2.2):

- the declining radioactivity of the waste – although, as noted in Chapter 2, spent fuel and some other long-lived wastes remain hazardous for extremely long times;
- the time of occurrence of peak calculated doses or risk;
- the need for adequate coverage of very slow long-term processes and infrequent events; and
- the need to address the concerns of stakeholders.

Box 5.5: **Factors that may be taken into account – in addition to increasing uncertainty – in setting the time frame covered by assessment modelling**

The declining radioactivity of the waste

Radioactive decay, which is well understood over virtually indefinite timescales, reduces the potential doses due to external irradiation and to ingestion or inhalation of radionuclides if isolation and containment were to be compromised.

The time of occurrence of peak consequences

Some regulatory criteria are primarily concerned with the magnitude of any releases of radioactivity from a repository, irrespective of when this occurs (Section 3.3). Such regulations require assessment calculations to be continued at least until the time of occurrence of peak consequences. As discussed earlier, geological repositories are sited and designed to provide prolonged isolation and containment of radioactivity, and a direct consequence of the isolation and containment strategy is that any release that eventually does occur may take place only in the distant future (see e.g. Figures 5.8). Thus, assessments of peak consequences may need to contend with significant uncertainties. Where such regulations exist, it is generally the responsibility of the implementer to demonstrate not only that peak consequences satisfy relevant regulatory criteria, but also that relevant uncertainties have been identified and appropriately considered in safety assessments.

The need for adequate coverage of slow processes and infrequent events

The processes and events affecting repository evolution and performance occur over a wide range of timescales (Appendix 4, observations from responses to Question 6.1a). Some, such as major climate changes, may be infrequent, and others, such as erosion processes, may be slow. Over a sufficiently long period, however, they may perturb the repository and its safety functions. A consideration in determining the overall time frame for safety assessment modelling is therefore that it should be sufficiently long that the impact of slow processes and infrequent events is explored or dealt with adequately.

The need to address the concerns of stakeholders

Safety assessment modelling should, as far as possible, address a timeframe that is sufficient to satisfy the concerns of stakeholders. The word stakeholders, as used here, includes all parties with any interest in the repository, including those who may be opposed to it. Stakeholders may have highly diverse concerns and expectations. As a general observation, for example, the public tends to be more concerned with the nearer that the far distant future.

5.3 Lines of argument complementary to quantitative modelling

Given that the some wastes present a potential hazard very far into the future, some further argumentation is sometimes required in safety cases beyond the time frames covered by safety assessment modelling. While a safety case will generally address the period over which anything defensible can be said about protection (a million years or more for a well-chosen site and design), the type of argumentation for safety that is appropriate at such distant times is an issue requiring further consideration.

As noted in the context of safety indicators, the limitation or attenuation of releases, which tends to be the focus of safety assessment modelling, is only one of the safety functions of a repository. A safety case also requires arguments to show that the potential likelihood and/or consequences of human intrusion are small and that the waste will remain isolated from humans while a significant potential hazard remains or while regulations require protection to be provided. Thus, lines of argument that are complementary to the results of release calculations, based, for example, on the absence of resources that might attract inadvertent human intrusion and on the geological stability of the site, with low rates of uplift and erosion, are required not only to compensate for increasing uncertainties affecting calculated releases at distant times, but also to address other aspects of safety at all times considered in the safety case.

The geological stability of a well-chosen site can be used to argue, for example, that uplift and erosion will not lead to exposure of the waste at the surface over timescales often in the order of millions of years or more. The safety case may rest predominantly or solely on such arguments at times when models and databases used to evaluate releases are judged to be inapplicable (e.g. Time frame 5 in Figures 5.1 and 5.7), as acknowledged in some regulations – see Section 3.3. Even these arguments cannot, however, be extended indefinitely into the future. Another line of argument is based on a comparison between the safety provided by geological disposal in the far future and that provided by other possible waste management strategies.

A few national programmes, such as Switzerland, have given some consideration to the possible loss of isolation (i.e., exposure of the waste at the surface, for example, from uplift and erosion) and its possible implications for external irradiation. These scenarios occur at the outer limits of the time periods covered by most national safety cases; the motivations and need for considering them depend on the on the geological setting and regulatory requirements.

Some programmes have argued that once the radiological toxicity of spent fuel on ingestion becomes comparable to that of natural uranium ore bodies, it no longer represents an "unusual hazard" in this respect. Figure 5.9, which is taken from the safety report of the Swiss Project Opalinus Clay (Nagra 2002), shows how the radiotoxicity index (RTI, as defined in Box 5.5) of different radioactive waste types decreases with time and that, after about a million years, the RTI of even the most toxic of the waste types, spent fuel, has dropped well below that of a volume of natural uranium ore sufficient to fill the emplacement tunnels of the repository considered in this study. Comparisons of this type (see also Hedin 1997) can be used to argue that, over a sufficiently long timescale, radioactive waste is comparable to natural features, such as ore bodies at the surface or underground, at least in terms of radiological toxicity via ingestion.

Box 5.6: **Radiotoxicity index**

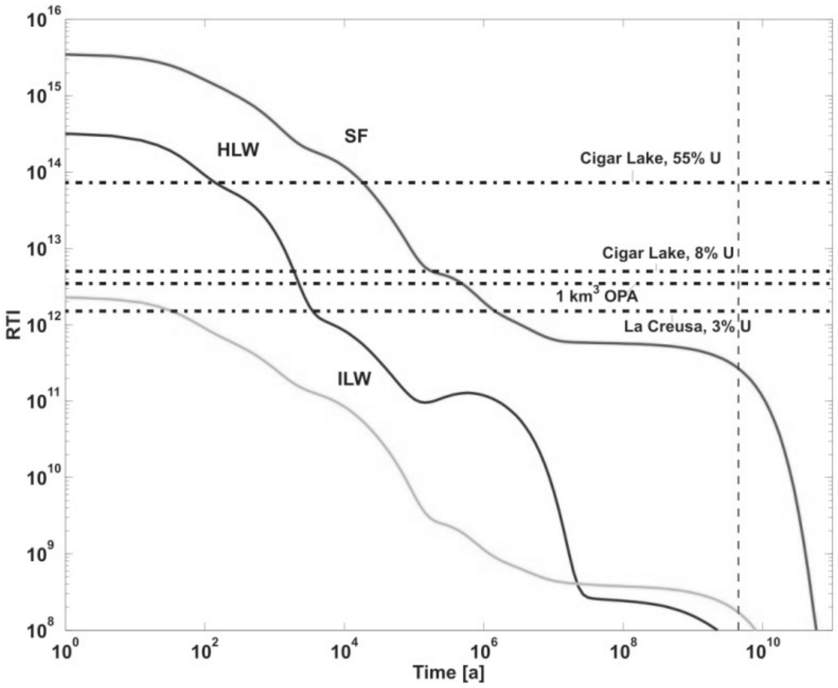
The radiotoxicity index (RTI), as used in Figures 5.9 and 5.13, is defined as the hypothetical dose, summed over all radionuclides, resulting from the ingestion of the activity A_j [Bq] at a given time divided by 10^{-4} Sv (derived from the Swiss regulatory annual dose limit):

RTI = $\Sigma A_j F_j / (10^{-4}\ \text{Sv})$, where F_j [Sv Bq^{-1}] is the dose coefficient for ingestion for radionuclide j (see Appendix 3 of Nagra 2002).

The uncertainty in the evaluation of RTI is well understood. In particular, most relevant half-lives are well known. There is uncertainty in the conversion of concentration in water and food to an effective dose equivalent, but that uncertainty is generally understood and reasonably quantifiable. Assuming that human beings, as we know them today, exist in the future, the uncertainty in the dose calculations used to generate figures such as Figure 5.9, given concentrations of radionuclides in foodstuffs, water, and soil, is independent of the evolution of the repository, its geological environment, the biosphere, and future human actions.

These arguments, however, also have their limitations. Even when the RTI or other indicators suggest 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. Not all natural systems are “safe”, and furthermore there can be important differences between natural systems and repositories, e.g. in the isotopes that are present, in their concentrations and in their mobility (Appendix 4, observations from responses to Question 9.1b). Such arguments also often do not address the issue of the potential hazard from external radiation (especially from artificial isotopes) in the absence of shielding if the waste were exposed (Section 2.2).

Figure 5.9: **Radiotoxicity index (RTI) of spent fuel (SF), vitrified high-level waste (HLW) and long-lived intermediate-level waste (ILW) as a function of time, in comparison to that of Opalinus Clay (OPA – the repository host rock) and to that of three different natural uranium ores (figure presented by Nagra at 7th IGSC meeting, 12-14 October 2005 – see Nagra, 2002 for details of the comparison)**



Note: In order to put the timescale shown in the figure in perspective, the vertical dashed line at 5 × 10^9 years indicates the time at which it is thought that the sun will become a red giant (e.g. C.J. Hogan: “Why the universe is just so”, Rev. Mod. Phys. 72(4), 1194, October 2000)

5.4 Presenting the safety case

5.4.1 Tailoring the documentation of the safety case to the target audience

Although the primary audience when presenting a safety case is often considered to be the regulator, there are also other stakeholders with an interest in the safety case. These include political decision makers and members of the public (such as local stakeholders), as well as technical specialists advising external groups and organisations, or the personnel of the implementing organisation itself. The primary audience may vary according to the stage reached in repository planning and development (e.g. Figure 5.10). At all stages, however, in order to build confidence on the part of the various stakeholders, a safety case needs to be presented in a style that is understandable and useful to its intended audience.

Multiple levels of documentation may be required, ranging from detailed technical reports designed to record all key assumptions and data in a traceable manner to more accessible forms such as brochures and video presentations. All of these documents and presentations describe aspects of only one safety case. The style, level of detail, arguments and time frames emphasised can, however, be tailored to the target audience, as illustrated in Figure 5.10. This may require consulting with different audiences in order to understand and clarify their interests, concerns and level of technical knowledge. Their concerns can be different for the different time frames considered in a safety case (NEA, 2002).

Figure 5-10: **Example of key features of the documentation of the safety case at different stages of a programme (figure presented by Nirex at 7th IGSC meeting, 12-14 October 2005)**

Stage in stepwise programme	Primary audience[1]	Dialogue focus	Technical focus	Assessment approach	Assessment end points	Presentation
Options	Government policy makers, scientific community, NGOs, public	Evaluation criteria and feasibility of waste management options	Developing and comparing waste management options, strategic environmental assessment of options	Understanding of processes, identification of hazards and issues (FEPs) and scoping calculations of potential impacts	Qualitative arguments, estimates of hazards (e.g. peak dose/risk), viability of options in context of regulatory criteria	Clear written/visual explanations of processes and assessment approach, with illustrative calculations
Siting strategy	Government policy	Inputs to methodology, e.g. scenarios and values for site evaluation criteria	Developing methodology and assessment criteria, identifying site-discriminating factors	Generic scenarios and ‘what if?’ calculations for specific timeframes	Fluxes, doses, conditional risks, comparisons with natural and anthropogenic analogues	Explain how assessments will be used within waste management programme and for site evaluation
Site evaluation	Government advisors, local communities, regulators	Sites for consideration and site comparisons, implications for local communities	Evaluation of sites	Conservative scoping calculations based on available site-specific data, exploring site-discriminating factors	Fluxes, doses, risks, groundwater return times, environmental concentrations	Highlight site-specific features, references to outstanding issues and future work
Detailed investigation at site(s)	Local authority representatives, local community, funding body, scientific community	Scientific/technical progress, resolution of outstanding issues	Building understanding of site characteristics, input to site investigation programme, optimisation of facility design	Increasingly detailed calculations in iterative assessment of site, identifying and resolving significant uncertainties, often using probabilistic methods	Environmental impacts and long-term dose/risk impacts	Hierarchical series of reports documenting research and analysis, with high-level summary of key points
Implementation	Regulators, local authority representatives, local community	Evidence for public inquiry	Authorisation submission, demonstration of compliance with Regulations	Rigorous quantitative assessment, full scenario analysis with weightings	Environmental statement, risk to potentially exposed groups, sysematic evaluation against other regulatory requirements	Part of full safety case, structured documentation with hierarchical presentation

[1] Those for whom the PA is primarily written. Many groups, including the public, will influence the decision-making process at each stage and will require information about the PA in appropriate formats. Regulators and waste producers are also important audiences at each stage due to their on-going roles.

In the case of a safety report aimed at communicating the safety case to the regulator, the regulator may itself provide an outline of what is expected. An example is the US NRC Yucca Mountain Review Plan (US NRC, 2003), which gives a detailed account of how each element of the case will be evaluated and judged. More often, however, the structure and broad content of the safety report is left to the implementer to determine.

The following sections highlight issues that relate specifically to timescales, and discuss how to provide audiences with information and arguments that enable them to understand the issues and contribute to informed debate, with a particular emphasis on communicating timescales issues to non-specialist audiences.

5.4.2 Use and presentation of time frames

Earlier chapters have highlighted a trend to divide the post-closure period into discrete "time frames", that are characterised by particular types of phenomena or uncertainties, and for which particular types of safety indicators or arguments are most suitable. These time frames can be a central element when structuring the presentation of the safety case. In the interests of clarity, it can be beneficial to discuss each time frame in turn, including the characteristics of the system and how they evolve within a given time frame, uncertainties, and performance with respect to waste isolation and radionuclide containment and releases. When discussing the consequences of releases, related arguments (including, but not limited to, the presentation of safety indicators *vs.* time) can be presented for each time frame in turn as an alternative to presenting a curve of dose or risk spanning the entire period covered by an assessment.

For example, in the approach proposed by Nirex, the safety case provides, for each time frame, a description of the key events and processes operating, references to relevant natural analogues and other qualitative arguments to support and demonstrate understanding of these events and processes and, where appropriate, quantitative assessment of the radiological risks and other safety indicators applicable in that time frame. For the final time frame, which extends beyond the time frame covered by assessment modelling, it is proposed only to use qualitative arguments to argue that there is still a degree of assurance of continuing safety.

It is important to emphasise (e.g. in presentation to technical audiences) that the role of the system components and safety functions may change over time, as described in Chapter 3, and not all components are required or expected to contribute to containment and/or isolation in all the time frames.

The level of detail of discussion may vary between time frames. This can reflect the level of understanding that is available, the complexity of the events and processes that operate or the interests and concerns of the target audience. Emphasis on certain time frames can also be a result of regulations (Finnish, Swedish and US regulations have been noted to be in this category in previous sections), and in such cases it is important for the regulator to explain and justify the way the regulations are structured to provide protection through requirements that change with time. The implementer must be familiar with, and be able to both explain and support, the justification for the time-dependent aspects of regulations. No confidence is to be expected on the part of an external audience if there appears to be a disagreement over the fundamental concept and definition of what is safe between the implementer and the regulator.

The handling of uncertainties that are most relevant to safety in each time frame needs to be explained by the implementer, including the use of conservatism and the meaning to be assigned to results (see the discussion in Section 5.2). At early times, for example, key uncertainties may relate to transient processes that could compromise the integrity of waste containment (although the impact of these uncertainties may be mitigated by the potential of the engineered barrier system and geosphere to retain any releases, even if early containment failure were to occur). At later times, critical uncertainties may relate more to transport and retention processes in the engineered barrier system and geosphere.

As noted earlier, in describing a safety case employing or emphasising various safety indicators in different time frames, it must be explained that this does not necessarily mean that different levels of protection are sought in different time frames. Rather, it is a reflection of the evolution of the system, with shifting emphasis, for example, on different barriers and safety functions, and the increase in uncertainty that tends to arise over time.

5.4.3 Time frames in perspective

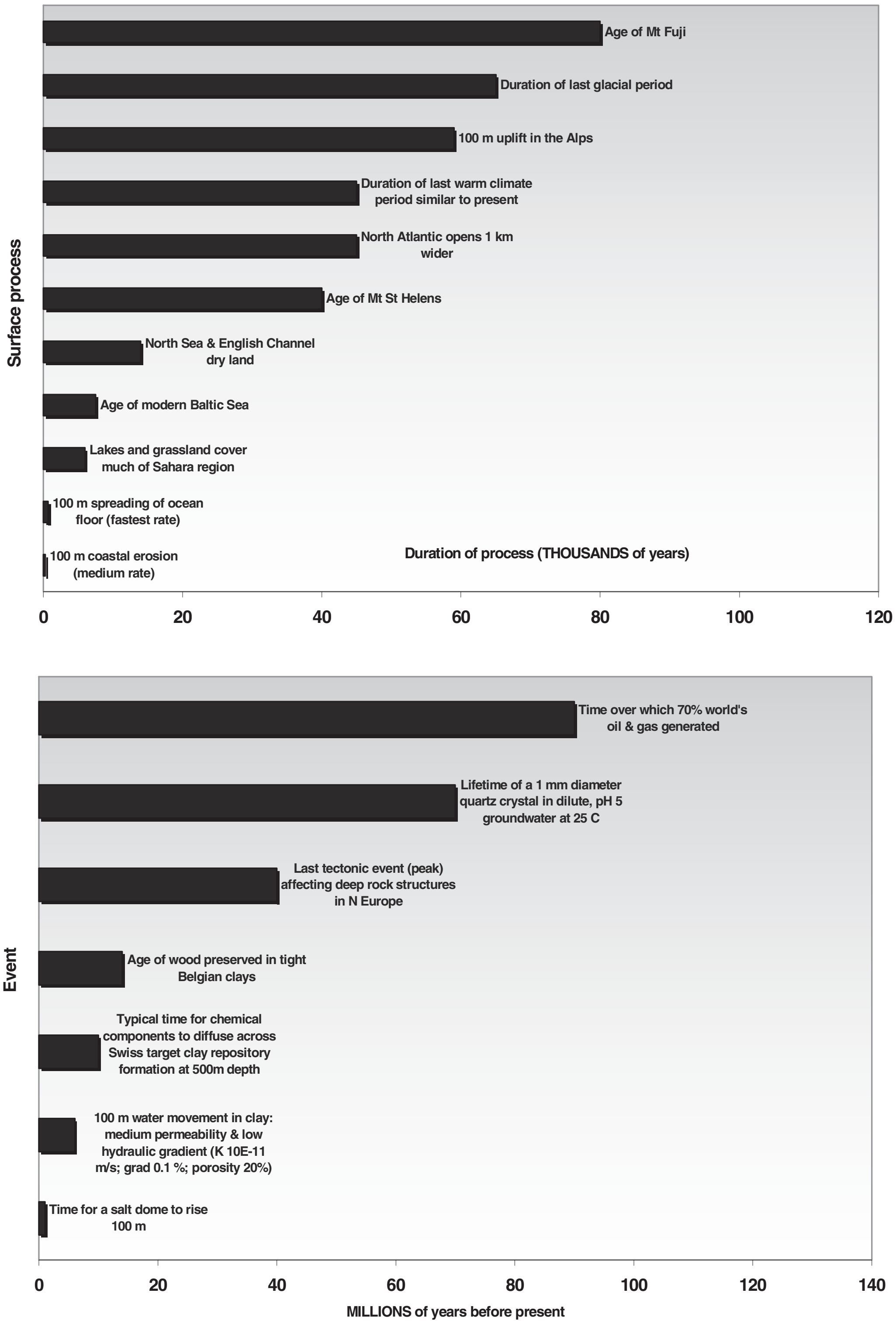
It can be useful to put in perspective the time frames addressed in the safety case by comparing them with perhaps more understandable past time frames. Four examples are given in Chapman (2002):

- Some disposal programmes countenance a measure of control over a repository site for a few hundred years, possibly even leaving a repository open to allow for ease of retrieval of waste if required (Chapter 4). This period is presumably to be managed by national institutions. It is, however, worth noting that 300 years ago, about one half of today's European nations did not exist (Figure 5.11).
- The whole of recorded human history happened in the last 5 000 years: about the time some concepts expect their waste containers to last.
- Human beings are believed to have first appeared in Africa perhaps 200 000 years ago (McDougall *et al.,* 2005): about the time it takes for spent fuel to reach the "cross-over" to radioactivity and toxicity levels similar to the original uranium ore (Figure 5.9).
- Human beings did not reach Europe until 40 000 years ago: in some deep clay formations, it takes water this long to move one metre.

A wide range of natural processes is also known to have affected the surface environment over time frames less than or comparable to those considered in safety cases (Figure 5.12a). On the other hand, the much longer time frames of some geological phenomena can be used to illustrate the stability of well-chosen geological environments (Figure 5.12b).

Figure 5.11: **European political boundaries 500 years ago (N. Chapman, private communication – redrawn after information in "The Times History of Europe" 2001)**

Figure 5.12: **Examples of past time frames relating to geological phenomena affecting (a), the surface, and (b), the environment deep underground, that could be used to put in perspective the time frames addressed in safety cases (from Figure 2.9 in Chapman & McCombie, 2003)**



Such comparisons can both help the audience grasp the magnitude of the timescales involved and, in the case of comparisons illustrating the slowness or infrequency of geological phenomena operating at repository depth, contribute to the plausibility of making prognoses over, say, a million year time frame.

Chapman points out, however, that these types of comparisons of past and future times give mixed messages:

> *"different people will feel reassured ("who really cares about times beyond comprehension") or worried ("how can we say anything at all about the future"), emphasising that, although people are clearly more worried about the near future, perceptions of long time scales vary considerably."*

Some audiences, especially those not in favour of a particular disposal project, will interpret the type of arguments made by Chapman in the four bullets listed at the start of this section as an attempt to lull them into complacency over long-term safety concerns. This point of view is value-driven and basically says that we do not have the right to do anything today that may present a real danger to unsuspecting people living in the future. Being a value judgement, it is a point of view that cannot be argued against using technical data or information. However, it is precisely such values that are addressed by regulations, taking account of the balance of future public safety with current societal needs for safety and managing resources, and with what is reasonably achievable in terms of cost and technology.

5.4.4 Importance of explaining protection at early times

In all geological disposal concepts, any releases of radioactivity to the human environment are expected only in the distant future. Most engineered barrier concepts for spent fuel and vitrified high-level waste, for example, are designed to provide an initial period of complete containment over a time frame of at least a thousand years and often considerably longer. Any releases from the engineered barriers that do occur will be limited in magnitude, for example, by the stability of the waste forms, by low solubilities, by slow transport within the engineered barriers and contained by, or greatly reduced by, slow transport through the geosphere.

These are highly robust arguments for safety when the radiological toxicity of the waste is at its highest. This early period may also be the period of most 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, as well as EC's RISCOM-2 project[1]). Chapman (2002) notes that:

> *"Most people are seriously concerned about the safety of future generations no further than their grandchildren: less than a 100 year time frame. A recent study of public opinion in Japan, UK and Switzerland (Duncan, 2001) showed that 75-80% of people who were questioned thought only this far forward when considering the future welfare of themselves and their family, and more than 90% only looked as far as 500 years into the future. The latter time horizon was also cited by more than 90% of people when considering a wider social perspective: the future welfare of their township. 80–90% of Swiss and UK respondents asked about their time scale of concern for the global environment stopped at 1 000 years."*

Thus arguments for safety and robustness of a geological repository in the early period (a few hundred to a thousand years, say) can usefully be emphasised when presenting the safety case to the

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

general public. On the other hand, the experience of the Konrad hearings shows that a rather general concern exists about the credibility of assessments as a whole, as well as very specific concerns about issues in the (very) short term, e.g. loss of property value, disturbance by waste transportations, safety of the present and the next one or two generations (Appendix 4, observations from responses to Question 10.2b). Andra identified similar concerns during its public and other authority's hearings, where operational safety was the focus of much attention.

Over longer time frames, the isolation and containment provided by a repository can be highlighted in safety case documentation using presentational techniques that emphasise that most of the activity of the waste decays within the system, in addition to more conventional dose or risk curves, for example, that emphasise releases. One such presentational technique is shown in Figure 5.13. The figure shows the results of a calculation of radionuclide release and transport from vitrified high-level waste packages in the repository analysed in the Swiss Project Opalinus Clay (Nagra, 2002). Rather than expressing the results as releases, however, Nagra has here shown the results in terms of the radionuclide inventory contained within different system components as a function of time. Inventory is expressed as a radiological toxicity index on ingestion (RTI, as defined in Box 5.5). The line "total" is the total radionuclide inventory in the waste form, itself (glass matrix), in the buffer in the form of precipitates, sorbed on buffer pore surfaces and in aqueous form, in the Opalinus Clay host rock and outside these barriers. The other lines show the different parts of this total in each of these barriers or forms as functions of time. The figure shows that radiological toxicity on ingestion is contained predominantly within the glass matrix for about 100 000 years. Eventually, after about ten million years, about 10% of the total RTI is contained in the Opalinus Clay, but by this time the total has declined by radioactive decay by about five orders of magnitude.

5.4.5 Building confidence in long-term stability and overall safety

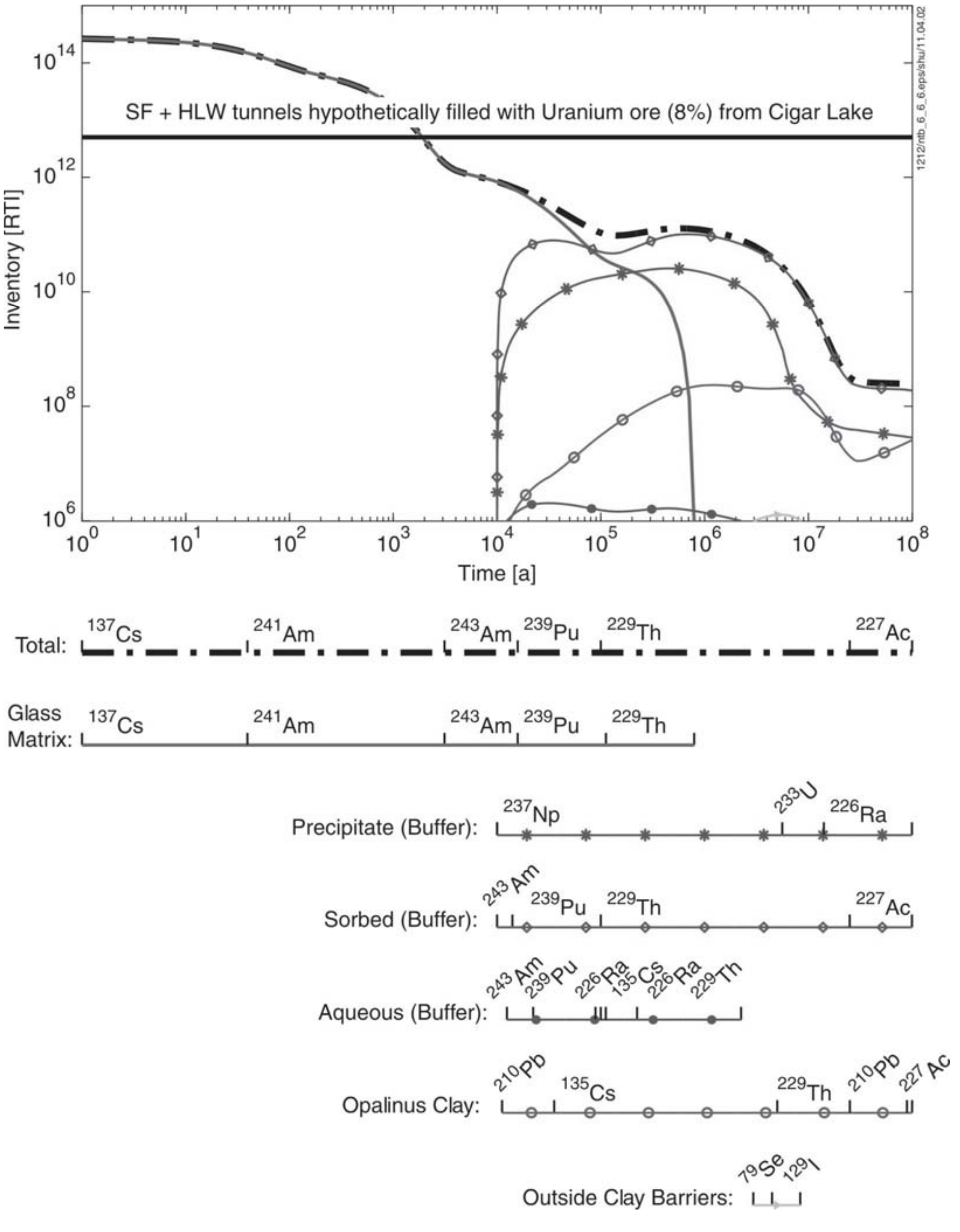
On several occasions, members of the public have shown a strong interest in events and situations that are expected to occur, if at all, only in the distant future, such as large seismic events, glacial cycles and volcanism. Highlighting accessible arguments for long-term geological stability, the stability of engineered barrier components and overall safety (below) is thus also an important aspect of building public confidence. For example, less quantitative evidence for long-term stability, including evidence from site characterisation, site history and natural analogues, may be more accessible, more convincing and of more interest than, say, the results of complex mathematical models.

The long-term stability and isolation potential of the geosphere is a key element in all safety cases for geological repositories. Arguments for the long-term stability of the geosphere based on evidence for a prolonged and uneventful geological history at a site can be both persuasive and accessible to non-specialists, as can arguments for containment based on the age and limited mobility of groundwater in host formations. "Natural experiments" can be valuable in this context. An example is the development of concentration profiles of naturally occurring isotopes and elements in the pore water of the Opalinus Clay, which is currently being considered as a potential repository host rock in Switzerland (Nagra, 2002). These provide evidence for slow, diffusion-dominated transport over long timescales in the past – hundreds of thousands to millions of years – as well as significant spatial scales – hundreds of metres or more.

The use of natural and anthropogenic (human artefact) analogues as evidence for the long-term stability of the waste forms (uranium and glass) and engineered barrier materials such as copper, iron, bentonite and cement, complementing data from experimental studies, has been mentioned earlier in this chapter. The public is familiar with situations where materials such as iron corrode quickly. Drawing their attention to situations where, say, Roman nails have survived largely uncorroded over a

1 000 year timescale is thus helpful in building confidence in the use of iron as a canister material, provided it can be shown that the conditions that provided stability in the analogue will also be present in the repository (of course, the limitations of such analogues also have to be acknowledged).

Figure 5.13: **The evolution and distribution of radionuclide inventory from high-level waste in the different components of a repository system, expressed as radiological toxicity on ingestion (RTI) (figure presented by Nagra at 7th IGSC meeting, 12-14 October 2005)**



Note: Bars beneath the graph indicate the radionuclides that make the highest contribution to RTI at any particular time and in any particular part of the system.

As noted earlier, the broad conclusion of safety assessment studies that safe geological disposal is feasible is further supported by natural analogue studies, which confirm that major geochemical anomalies (ore bodies) can be preserved for hundreds of millions of years in suitable geological settings. Examples are the Cigar Lake uranium ore body in Canada (Cramer & Smellie, 1994) and the Oklo natural reactors in Gabon (CSN, 2004). The Oklo analogue illustrates that even many of the "artificial" isotopes produced in nuclear reactors can be effectively isolated until they decay completely.

In the case of the proposed unsaturated zone repository at Yucca Mountain in the United States, the Peña Blanca natural analogue in Chihuahua, Mexico, has given information showing that experiments on the oxidation of uranium dioxide in the laboratory have produced the same secondary mineral suites encountered in the comparable natural setting in that analogue, suggesting there is no need to prolong such experiments to test for further changes in the secondary minerals observed. In addition, the very weak downstream uranium and minor radionuclide signature in the saturated zone away from the uranium ore body at this site argues for the conservative nature of a model for Yucca Mountain, which, when applied at this analogue site, suggested there should be stronger chemical signatures in the groundwater (for a general discussion of this analogue and the work performed there by both the US Nuclear Regulatory Commission (US NRC) and US Department of Energy (US DOE), see Bechtel-SAIC, 2002).

In discussing the timescales addressed by the safety case, these types of evidence can be useful in that they show that these timescales are not unusual in natural and man-made systems, many of which have been extensively studied and are well understood. In the case of analogue evidence, the explanation of why the analogue has survived over a prolonged period, and why similar conditions will prevail in the case of a repository, is as important as the existence of the analogue itself. Without such concept-specific explanations, the idea that there are counter-analogues for every analogue used takes hold easily and brings into question the objectivity of those presenting a safety case.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Refinement of understanding of key issues related to timescales coming from this work

The first aim of the present report was to provide a review of the current status and ongoing discussions on the handling of issues related to timescales in the development and presentation of safety cases for geological repositories. The report is considered to be state of the art, drawing directly on input from a wide range of implementing organisations, regulators and scientific and technical institutes and advisory bodies, primarily through their responses to a questionnaire, but also through subsequent meetings and discussions.

The various issues discussed in the earlier "lessons learnt" report (NEA, 2004a) have been revisited, and additional areas such as the planning of pre- and post-closure actions have been discussed. For some issues, current understanding is unchanged compared to the 2004 document, whereas for others, some differences can be identified, as described below.

a. The timescales over which the safety case needs to be made

The 2004 document argued that ethical considerations imply that the safety implications of a repository need to be assessed for as long as the waste presents a hazard. The present report recognises that there are different and sometimes competing ethical principles that need to be balanced. It seems that the discussion of how to come to a balanced and socially acceptable view is still at an early stage in many nations and internationally. In addition, this discussion should be informed by inputs from a wide range of stakeholders, which is beyond the remit of the working group that produced this report.

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

Both the 2004 document and the present report reflect a view that the limits to the predictability of the repository and its environment need to be acknowledged in safety cases.

c. Arguments for safety in different time frames

Both the 2004 document and the present report note that the types of argument and indicators of performance and safety used or emphasised may vary between time frames. The present report cites ongoing developments in the approaches to partition future time into time frames and developments in phenomenological and safety function analyses in different time frames. The 2004 document observes that regulations are increasingly providing guidance on the use of lines of argument that are complementary to dose and risk. This observation is confirmed in the present report in the discussions of recent regulations and draft regulations in Sweden and the United States. The present document emphasises that complementary lines of argument are useful, not only to compensate for increasing uncertainties affecting calculated releases at distant times, but also to address other aspects of safety, especially continuing isolation, at all times. Complementary arguments might be based, for example, on the absence of resources that could attract inadvertent human intrusion and on the geological stability of the site, with low rates of uplift and erosion. The argumentation for safety in the very long term is, however, an issue of ongoing discussion that is likely to require a consideration of ethical principles, since it relates to our ability or responsibility to protect the environment in the very remote future.

d. Interpretation of dose and risk calculated in long-term safety assessments

Both the 2004 document and the present report note international consensus that doses and risks evaluated in safety assessments are to be interpreted as illustrations of potential impact to hypothetical individuals based on stylised, agreed sets of assumptions. The assumptions are site-specific and can vary significantly; for this reason, the calculated results from safety cases should be carefully analysed if they are compared among national programmes.

e. Complementary safety indicators and safety requirements

The 2004 document states that 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. Recent regulatory guidance cited in the present report shows that safety indicators and requirements are not only quantitative, but can include more qualitative concepts such as best available technique (BAT) and constrained optimisation. This issue of how to evaluate compliance with requirements expressed in terms of qualitative indicators may, however, require further consideration, as may the interpretation of optimisation of protection when dealing with impacts across different timescales.

f. Addressing public concerns

Both the 2004 document and the present report note that the period of a few hundred years following emplacement of the waste may deserve particular attention in documents aimed at the public. The present report makes a number of other specific recommendations regarding the communication of how safety is provided in different time frames.

6.2 Areas of consensus and points of difference

The second aim of the present report was to highlight areas of consensus and points of difference between national programmes. There appears to be a broad consensus on the broad types of ethical, technical and pragmatic considerations relevant to the issue of handling time scales in safety cases and regulations. There are, however, differences between programmes and nations, as well as some commonalities, regarding how they should be weighted or balanced, given that different objectives and considerations may sometimes compete. Thus, for example, some regulations set constant dose or risk criteria that apply without time limit, on the basis that responsibilities of the present generation to future generations extend equally and indefinitely into the future (intergenerational equity). There are, on the other hand, some more recent regulations that set criteria at later times that avoid what could be viewed as an undue burden of demonstration on the implementer. This may be done by setting criteria in terms of alternative measures of consequence that are less affected by irresolvable uncertainties in the far future.

Points of consensus or common practice and points of difference on how the various timescales issues are dealt with are summarised in Table 6.1a-c. Table 6.1a addresses issues in siting and design and in regulations for the long-term protection that the site and design must provide based on the discussions in Chapter 3, Table 6.1b addresses issues in the planning and regulation of pre- and post-closure actions based on Chapter 4 and Table 6.1c addresses issues in the making and presenting of safety cases based on Chapter 5).

6.3 Recommendations

The third aim of this report was to determine if there is room for further improvement in methodologies to handle timescales issues in safety assessment and in building and presenting safety cases. A review of the questionnaire responses and subsequent discussions did not come up with specific suggestions on safety assessment methodologies. Regarding the presentation of safety cases, however, the following recommendations are made:

a. Structuring

In the interests of gaining, sharing and showing understanding of a system as it evolves and performs over long timescales, it is useful to both define and develop means to address various time frames in a scientific and logical manner. Some programmes have advanced on this road, but more needs to be done. This is an area of likely future development.

b. Arguing safety at early times

There is a tendency in safety case documents to emphasise arguments for safety at later times – perhaps tens of thousands of years or more in the future – since this is when releases are most likely to take place. There are, however, very persuasive arguments for safety at early times (e.g. the first few hundred years after emplacement), consistent with the high radiological toxicity of the waste in this time frame, and it can be useful to emphasise these arguments, especially when presenting the safety case to non-specialist audiences, which are often (though not universally) most concerned by a time frame of this order.

c. Presenting timescales issues

In view of the importance to the safety case of timescales issues, and in view of the acknowledged differences between programmes and nations in how these issues are treated, it may be helpful to dedicate a specific section or sections of a safety report to explaining the handling of issues such as how to set a time frame for quantitative assessment, and explaining how uncertainties are treated (and whether this treatment varies with time), including how, for example, multiple safety and performance indicators are used and how the meaning to be attached to results may vary as a function of time.

d. Timescales in perspective

In the interests of communicating effectively with stakeholders and to build stakeholder confidence, it can be useful to place the time frames covered by the safety case in perspective by comparing with other, more familiar time frames (such as those suggested in Section 5.5.3). This needs to be done with caution since it could give the impression that the task of demonstrating safety over a time frame far in excess of those considered in most areas of human activity is over-ambitious or an unrealistic objective. Here, a clear explanation of the robustness of the geosphere and of key engineered components, based for example on natural analogues and the good understanding of stable geological environments over comparable (or still longer) time frames, can be valuable.

6.4 Final observations

A general observation from the timescales questionnaire responses is that, in many programmes, a significant part of the final responsibility for the handling of timescales issues in safety cases is assigned to the implementer. Apart from setting safety criteria (that may or may not vary over time), the regulator's task is generally to review and point out any difficulties in the approaches to the handling of timescales issues adopted by the implementer. Wherever the final responsibility lies, a dialogue between the implementer, regulator and other stakeholders is valuable in resolving the issues in a manner that is widely accepted, and such dialogue is ongoing in many programmes.

Although this document has shown that a great deal of consideration has been given to the handling of timescales in siting and design and in developing and presenting the safety case, some issues still require further clarification. In particular, as discussed in Chapter 2, while the long half-lives of some radionuclides means that spent fuel and some long-lived wastes can never be said to be harmless, there are practical limitations as to how long anything meaningful can be said about the protection provided by any system – the limit being between several hundred thousand years and several million years for many systems. Some programmes consider the treatment in safety cases of the residual hazard potential of the waste at times much greater than a million years to be an issue that is yet to be resolved. These issues are currently being addressed by the Long-term Safety Criteria (LTSC) initiative of the NEA Radioactive Waste Management Committee (RWMC).

In conclusion, the range of timescales that needs to be addressed within our safety cases presents considerable challenges. The decreasing demands on system performance as a result of the decreasing hazard associated with the waste with time partly offset the demands that increasing uncertainty (and decreasing predictability) place on safety assessment. Nevertheless, as discussed throughout this report, while some hazard may remain for extremely long times, increasing uncertainties mean that there are practical limitations as to how long anything meaningful can be said about the protection provided by any system against these hazards. Thus, time and level of protection – and assurance of safety – are linked to one another. These practical limitations need to be acknowledged in safety cases.

The various methods and approaches discussed in this report demonstrate that there is a range of approaches available now that can be called upon for developing and presenting safety cases. Furthermore, this is an area of considerable interest to all national programmes and is likely to be the subject of further developments in the future.

Table 6.1a: **Summary of the handling of issues in siting and design and in regulations for the long-term protection that the site and design must provide (based on the discussions in Chapter 3)**

Issue	Consensus, common practice and trends	Points of difference
Providing long-term isolation and containment	Need to achieve robustness through siting and designing for: passive safety; multiple safety functions (see below); stable and predictable system components or barriers, particularly the geological environment. Emerging preference for expressing how a repository provides safety as a function of time in terms of evolving safety functions (rather than in terms of barrier evolution).	National regulatory criteria regarding: the period over which host rock stability must be demonstrated; whether perturbing events such as earthquakes necessarily preclude a site.
Roles of the barriers and safety functions as functions of time	Isolation as a key safety function of the geological environment throughout the post-closure period. Aim of containing the major part of the radionuclide inventory within the repository and its immediate surroundings. Trend towards greater awareness of the difficulties in fully characterising heterogeneous host rocks. Design for substantially complete containment of radionuclides during the spent-fuel/high-level waste "thermal phase".	Whether or not the geosphere is the only barrier that can be relied upon at distant times to provide containment/attenuation of releases. Contribution of the engineered barriers and geosphere transport barrier to the safety case in different time frames. Whether substantially complete containment of radionuclides during the spent-fuel/high-level waste "thermal phase" is a regulatory requirement.
The levels of protection required in regulation as a function of time	Recognition in regulation on the impossibility of precise prediction and a requirement to assess the impact of uncertainties. Recognition of calculated dose/risk as measures of protection, rather than predictions. Avoidance of detailed specification in regulation of requirements on system components. Broad similarities in quantitative regulatory safety criteria up to 10 000 years. Some recent regulations specify different criteria in different (later) time frames.	Whether quantitative regulatory criteria apply without time limit, or are limited to a million years (i.e. in Sweden and in draft EPA regulations for Yucca Mountain in the US) or other specific time frame Whether the weight given to calculated risk and dose for compliance demonstration decreases with time (increasing emphasis on BAT at later times in Swedish regulations). Specification by the Finnish regulator of geo-bio flux constraints beyond 10 000 years. Proposal in draft EPA regulations for Yucca Mountain in the US to apply a higher (though still protective) dose limit beyond 10 000 years compared to that prior to 10 000 years. The degree to which a more detailed assessment of uncertainties is required by regulation at earlier times compared to later times.

Table 6.1b: **Summary of the handling of issues in the planning and regulation of pre- and post-closure actions (based on the discussions in Chapter 4)**

Issue	Consensus, common practice and trends	Points of difference
Impact of an extended open period on post-closure safety	Ensuring that the pre-closure phase has no unacceptable long-term impact of on post-closure safety is an objective in repository planning. Disturbances caused by any open period of the safety-relevant characteristics of the system must be assessed as part of a safety case.	Duration of the pre-closure phase and the degree to which an extended open period is foreseen.
Monitoring and post-closure actions	Pre-closure monitoring is an essential part of compiling a database for repository planning and safety case development No monitoring or other post-closure actions should be undertaken that could undermine isolation and containment. The possibility of remedial actions taken as a result of post-post-closure monitoring should not form part of a safety case. Post-closure monitoring and active control of a repository cannot be assumed (in a safety case) for more than around a hundred years. It is nevertheless reasonable and prudent to plan to extend monitoring and controls as long as possible, taking into account funding and other constraints (e.g. for the purposes of public reassurance; defence in depth). Records may be assumed to exist over a longer period, but credit for these as a deterrent to human intrusion is limited to around a few hundred years.	The nature of the monitoring and controls that are foreseen. Whether regulations specify the time frame over which monitoring, control and record keeping should be maintained. Whether regulations specify the time frame over which human intrusion can be excluded in a safety case as a result of such actions.

Table 6.1c: **Summary of the handling of issues in the making and presenting of safety cases (based on the discussions in Chapter 5) (continued over page)**

Issue	Consensus, common practice and trends	Points of difference
Understanding how a repository and its geological environment evolve	Importance of synthesising information from a wide range of sources, including studies of site history, natural tracers and natural and anthropogenic analogues. Identification of relevant events and processes as a task for the implementer. Use of sensitivity analysis to identify key uncertainties. Trend towards formal methods to address repository evolution in as scientific and logical a way as possible. Trend towards using time frames to facilitate the making and presentation of the safety case. Identification of reserve and latent safety functions, and their use as lines of argument in a safety case.	Whether or not the regulator specifies events and processes that should, as a minimum, be considered for inclusion in a safety case. Whether or not more widespread use of analogues would be feasible and justified. Basis for discretising future time into time frames and types of division (sequential vs. overlapping and nested time frames, etc.).
Safety assessment modelling	Common practice that safety assessment modelling (and safety indicators) tend to focus on containment/releases rather than isolation. It is for the implementer to justify which events and processes to include in assessment models, and how to represent them in the models. Modelling results are indications or illustrations of potential levels of protection - not predictions. Stylised modelling is appropriate for the biosphere, impact of climate change and human intrusion. The development of more realistic treatment of time dependency in assessment models is a potential area for model enhancement. Trend towards evaluating, in addition to dose and risk, additional safety indicators, and emphasising these more at later times when the assumptions underlying dose and risk calculations become more difficult to support (e.g. following the recommendations of SPIN). A million years as a commonly accepted upper time limit for assessment modelling in recent safety assessments.	Whether an overall assessment time frame is specified in regulations (see also Table 6.1a). Whether or not the increasing simplification and stylisation of assessment models with time is reflected in national regulations. Whether or not the regulator takes upon itself the responsibility for defining stylised assumptions (e.g. for biosphere modelling). Treatment of the correlation between the impact of climate change on the underground environment, on the biosphere and on human lifestyles (the extent to which these are decoupled). Definition in Finnish regulations of geo-bio flux constraints (reference values for complementary safety indicators are generally left to the implementer to define). Value of presenting results at times when uncertainties call into question most of the assumptions made in evaluating radionuclide releases.

Table 6.1c: **Summary of the handling of issues in the making and presenting of safety cases (based on the discussions in Chapter 5) (cont'd)**

Issue	Consensus, common practice and trends	Points of difference
Lines of argument complementary to quantitative modelling	Trend towards emphasis on geological stability as a safety argument in the furthest future (e.g. beyond a million years) – if such time frames are not excluded from consideration by regulations (table 6.1a).	The value of comparisons of radiotoxicity on ingestion with, for example, natural ore bodies
Presenting the safety case	See recommendations in the main text	The degree of regulatory guidance on the structure and content of the safety case.

6.5 References

AECL (1994), *Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste*. Atomic Energy of Canada Limited Report, AECL-10711, COG-93-1, Pinawa, Canada.

AkEnd (2002), *Site Selection Procedure for Repository Sites – Recommendations of the AkEnd – Committee on a Site Selection Procedure for Repository Sites (Arbeitskreis Auswahlverfahren Endlagerstandorte).*

Andra (2005a), Dossier 2005 Argile – *Tome : Évolution phénoménologique du stockage géologique-rapport Andra n° CRP ADS 04 0025, décembre 2005* (also available in English).

Andra (2005b), Dossier 2005 Argile – *Tome : Architecture et gestion du stockage géologique, rapport Andra n° C RP ADP 04 0001, Décembre 2005* (also available in English).

Andra (2005c), *Dossier 2005 Argile – Tome : Évaluation de sûreté du stockage géologique, rapport Andra n° C RP ADSQ 04 022*, (also available in English).

Bechtel-SAIC Company, LLC, (2002), *Natural Analogue Synthesis Report*, TDR-NBS-GS-000027 Rev 00, ICN 2, Las Vegas, Nevada, available on the Internet at: www.ocrwm.US DOE.gov/documents/amr/32310/32310.pdf.

Becker, D-A., Buhmann, D., Storck R., Alonso, J., Cormenzana, J-L., Hugi. M., van Gemert, F., O'Sullivan, P., Laciok, A., Marivoet, J., Sillen, X., Nordman, H., Vieno, T. & Niemeyer, M. (2002), *Testing of Safety and Performance Indicators (SPIN)*, Final Report, EUR 19965 EN.

Chapman, N.A. (2002), Long Timescales, Low Risks: Rational Containment Objectives that Account for Ethics, Resources, Feasibility and Public Expectations – Some Thoughts to Provoke Discussion, in *The Handling of Timescales in Assessing Post-closure Safety of Deep Geological Repositories*, Workshop Proceedings, Paris, France 16-18 April 2002, OECD/NEA, Paris, France.

Chapman, N.A. and McCombie, C.M. (2003), *Principles and Standards for the Disposal of Long-Lived Radioactive Wastes*. Waste Management Series v.3. Elsevier (Pergamon), Amsterdam. 277 pps.

CNSC (2004), *Managing Radioactive Waste: Regulatory Policy*, Canadian Nuclear Safety Commission, P-290, Ottawa, Canada.

Cramer, J.J. and Smellie, J.A.T. (1994), *Final Report of the AECL/SKB Cigar Lake Analogue Study*, Atomic Energy of Canada Ltd. Report, AECL-10851, COG-93-147, SKB TR 94-04.

CSN (2004): *Analogue Application to Safety Assessment and Communication of Radioactive Waste Geological Disposal*. Illustrative synthesis, DID-11.04.

de Preter, P., Bel, J., Gens, R., Lalieux, P. & Wickham, S. (2005), "The Role of Safety Functions, Scoping Calculations and Process Models in Supporting the Choice of a Reference Design for Belgian High-level Waste and Spent Fuel Disposal," presented at the 3rd EBS workshop on

Integration of the EBS in a Safety Case: Role of Modelling, La Coruña, Spain, 24-26 August 2005.

DGSNR, FANC, IRSN, AVN, ANDRA, ONDRAF/NIRAS (2004), *Geological Disposal of Radioactive Waste: Elements of a Safety Approach.*

DSIN (1991), *Régle fondamentale de sûreté III.2.f*, Direction de la Sûreté des installations nucléaires, June 1991.

Duncan, I.J. (2001), *Radioactive Waste: Risk, Reward, Space and Time Dynamics*. Unpublished D. Phil Thesis, University of Oxford, United Kingdom.

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

Hedin, A. (1997) *Spent nuclear fuel – how dangerous is it?* SKB Technical Report TR-97-13, Stockholm, Sweden. www.skb.se/upload/publications/pdf/TR%2097-13webb.pdf

Helton, J.C. & Marietta, M.G. (2000), *The 1996 Performance Assessment for the Waste Isolation Pilot Plant. Reliability Engineering and System Safety*, 69, 1-3. New York, New York: Elsevier.

HSK & KSA (1993), Guideline for Swiss Nuclear Installations: Protection Objectives for the Disposal of Radioactive Wastes (*Schutzziele für die Endlagerung radioaktiver Abfälle, Richtlinie für schweizerische Kernanlagen*), Swiss Federal Nuclear Safety Inspectorate (HSK) and Federal Commission for the Safety of Nuclear Installations (KSA); HSK-R-21, HSK, Villigen, Switzerland.

IAEA (1989), *Safety Standards – Safety Principles and Technical Criteria for the Underground Disposal of High Level Radioactive Waste*. Safety Series No. 99, International Atomic Energy Agency, Vienna, Austria.

IAEA (1994), *INWAC Subgroup on Principles and Criteria for Radioactive Waste Disposal; International Atomic Energy Agency: Safety Indicators in Different Time Frames for the Safety Assessment of Underground Radioactive Waste Repositories: First report of the INWAC Subgroup on Principles and Criteria for Radioactive Waste Disposal.* IAEA-TECDOC 767, International Atomic Energy Agency, Vienna, Austria.

IAEA (1995), *The Principles of Radioactive Waste Management*, Safety Series No. 111-F, Vienna, Austria.

IAEA (1999*), Long-term Release from Solid Waste Disposal Facilities: the Reference Biosphere Concept*. BIOMASS Theme 1, Working Document No. 1, International Atomic Energy Agency, Vienna, Austria.

IAEA (2001), *Monitoring of Geological Repositories for High level Radioactive Waste*. IAEA-TECDOC-1208, International Atomic Energy Agency, Vienna, Austria.

IAEA (2003), *Safety Indicators for the Safety Assessment of Radioactive Waste Disposal. Sixth report of the Working Group on Principles and Criteria for Radioactive Waste Disposal*, IAEA-TECDOC-1372, International Atomic Energy Agency, Vienna, Austria.

IAEA (2005), *Natural Activity Concentrations and Fluxes as Indicators for the Safety Assessment of Radioactive Waste Disposal*, IAEA-TECDOC-1464, International Atomic Energy Agency, Vienna, Austria.

IAEA and NEA (2006), IAEA Safety Standards Series: Safety Requirements Number WS-R-4: *Geological Disposal of Radioactive Waste, jointly sponsored by the International Atomic Energy Agency and the OECD Nuclear Energy Agency*, published by the International Atomic Energy Agency, Vienna, Austria.

ICRP (1997), Annals of the ICRP 27 Supplement 1997, *Radiological Protection Policy for the Disposal of Radioactive Waste*, ICRP Publication 77, Pergamon Press.

ICRP (1990), Annals of the ICRP, 1990 R*ecommendations of the International Commission on Radiological Protection*, ICRP Publication 60, Pergamon Press.

ICRP (2000), Annals of the ICRP, R*adiation Protection Recommendations as Applied to the Disposal of Long Lived Solid Radioactive Waste,* ICRP Publication 81, Pergamon Press.

ICRP (2005a), *Assessing Dose of the Representative Individual for the Purpose of Radiation Protection of the Public*, Report by the ICRP Committee 4 Task Group on Definition of the Individual, Version 18.1, Draft for Consultation (web version).

ICRP (2005b), *The Optimisation of Radiological Protection - Broadening the Process*, Report by the ICRP Committee 4 Task Group on Optimisation of Protection, Revision 25, Draft for Consultation (web version).

JNC (2000), *H12 Project to Establish Technical Basis for HLW Disposal in Japan*, Supporting Report 3: Safety assessment of the geological disposal system, 2nd progress report on research and development for the geological disposal of HLW in Japan. JNC TN1410 2000-004. JNC, Tokai, Japan.

KASAM (2004), *Kunskapsläget på kärnavfallsområdet*, SOU 2004:67, Swedish National Council for Nuclear Waste, Stockholm, Sweden.

Kickmaier, W. & McKinley, I. (1997), *A review of research carried out in European rock laboratories, Nuclear Engineering and Design* 176, pp 75-81.

McDougall, I., Brown, F. H. & Fleagle, J. G. (2005), *Stratigraphic Placement and Age of Modern Humans from Kibish, Ethiopia*, Nature, Volume 433, Number 7027 (February 17th 2005), pp733-736.

Mazurek, M., Gautschi, A., Gimmi, T., Leu, W., Marschall, P., Müller, W., Naef, H. & Waber, H. 2004: "*Geological Stability: Learning from the Past to Predict Long-term Future Evolution, in Geological Disposal: Building Confidence using Multiple Lines of Evidence*," First AMIGO Workshop Proceedings, Yverdon-les-Bains, Switzerland, 3-5 June 2003, OECD/NEA, Paris, France.

Nagra (1994), *Kristallin-I Safety Assessment Report*, Nagra Technical Report 93-22, Nagra, Wettingen, Switzerland.

Nagra (2002), *Project Opalinus Clay: Safety Report*, Nagra Technical Report 02-05, Nagra, Wettingen, Switzerland.

NAPA (1997), *Deciding for the Future: Balancing Risks, Costs, and Benefits Fairly Across Generations*, National Academy of Public Administration, Washington DC, United States.

NEA (1995), *The Environmental and Ethical Basis of Geological Disposal*, OECD, Paris, France.

NEA (1997), *Lessons Learnt from Ten Performance Assessment Studies*, OECD, Paris, France.

NEA (1999a), *Geological Disposal of Radioactive Waste: Review of Development in the Last Decade*, OECD, Paris, France.

NEA (1999b), *Progress towards Geological Disposal of Radioactive Waste: Where do we Stand?* OECD, Paris, France.

NEA (1999c), *The Role of the Analysis of the Biosphere and Human Behaviour in Integrated Performance Assessments*, OECD PAAG document NEA/RWM/PAAG(99)5.

NEA (2000), *Radioactive Waste Management, Regulatory Review of Assessments of Deep Geologic Repositories: Lessons Learnt (IPAG-2 Report)*, OECD, Paris, France.

NEA (2002), *The Handling of Timescales in Assessing Post-closure Safety.* Workshop proceedings. OECD, Paris, France.

NEA (2003), *The French R&D Programme on Deep Geological Disposal of Radioactive Waste – An International Peer Review of the "Dossier 2001 Argile"*, OECD, Paris, France.

NEA (2003a), *Engineered Barrier Systems and the Safety of Deep Geological Repositories; State-of-the-art Report*, OECD, Paris, France.

NEA (2003b), *Proceedings of the First AMIGO Workshop on Building Confidence using Multiple Lines of Evidence*, Yverdon-les-Bains, Switzerland, 3-5 June 2003, OECD, Paris, France.

NEA (2004a), *The Handling of Time Scales in Assessing Post-closure Safety, Lessons Learnt from the April 2002 Workshop in Paris, France*, OECD, Paris, France.

NEA (2004b), *Post-closure Safety Case for Geological Repositories: Nature and Purpose*, OECD, Paris, France.

NEA (2004c), Integration Group for the Safety Case (IGSC), NEA/RWM/IGSC(2005)3, Topical Session Proceedings of the 6th IGSC Meeting, *The Role of Monitoring in a Safety Case*, held on 3 November 2004, Issy-les-Moulineaux, France.

NEA (2007), *Regulating the Long-term Safety of Geological Disposal, Towards a Common Understanding of the Main Objectives and Bases of Safety Criteria*, OECD, Paris, France.

Nirex (2003), *Generic Repository Studies: Generic Post-closure Performance Assessment*, Nirex Report N/080, Nirex, United Kingdom.

Nirex (2005), *The Viability of a Phased Geological Repository Concept for the Long-term Management of the UK's Radioactive Waste*, Nirex Report N/122, Nirex, United Kingdom.

NWMO (2005), *Choosing a Way Forward, the Future Management of Canada's Used Nuclear Fuel*, Final Study, NWMO, Toronto, Canada.

ONDRAF/NIRAS (2001), Technical Overview of SAFIR 2: *Safety Assessment and Feasibility Interim Report 2*, ONDRAF/NIRAS Report NIROND 2001-05 E, Belgium.

SKB (1999), *SR 97 – Post Closure Safety*, SKB Technical Report TR-99-06, SKB, Stockholm, Sweden.

SKB (2004), *Interim main report of the safety assessment SR-Can*, SKB Technical Report TR-04-11, Stockholm, Sweden.

SKI (1996), *SKI SITE-94, Deep Repository Performance Assessment Project*, SKI Technical Report 96:36, Stockholm, Sweden.

SSI (2000), *The Swedish Radiation Protection Authority's Regulations on the Protection of Human Health and the Environment from the releases of Radioactive Substances from Certain Nuclear Facilities*, issued on Dec. 15th 2000, SSI FS 2000:12, SSI, Stockholm, Sweden.

SSI (2005), *The Swedish Radiation Protection Authority's guidelines on the application of the regulations (SSI FS 1998:1) concerning protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste*, SSI FS 2005:5, SSI, Stockholm, Sweden.

STUK (2001), Guide YVL 8.4, *Long-term Safety of Disposal of Spent Nuclear Fuel, Radiation and Nuclear Safety Authority (STUK)*, Helsinki, Finland.

STUK (2003), Guide YVL 8.1, *Disposal of Low and Intermediate Level Waste for the Operation of Nuclear Power Plants, Radiation and Nuclear Safety Authority (STUK)*, Helsinki, Finland.

The Times History of Europe, Times Books, London, (2001).

UN (1992), *Report of the United Nations Conference on Environment and Development; Rio de Janeiro, 3-14 June 1992, Annex 1: Rio Declaration on Environment and Development*, A/CONF.151/26 (Vol. I).

US DOE (2002a), *Final Environmental Impact Statement for a Geological Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada*, US DOE/EIS-0250, Office of Civilian Radioactive Waste Management, Washington, D.C., United States, available on the Internet at: www.ocrwm.US-DOE.gov/documents/feis_2/index.htm

US DOE (2002b), *Yucca Mountain Site Suitability Evaluation*, US DOE/RW-0549, Office of Civilian Radioactive Waste Management, Washington, D.C., available on the Internet at: http://www.ocrwm.US-DOE.gov/documents/sse_a/index.htm

US EPA (2005), *Proposed Rule; Public Health and Environmental Radiation Protection Standards for Yucca Mountain*, Nevada, 40 CFR Part 197, Federal Register 70:161, pp. 49014-49065, US Environmental Protection Agency, Washington D.C., United States.

US National Academy of Sciences, National Research Council, 1995: *Technical Bases for Yucca Mountain Standards*, Washington, D.C., United States.

US NRC (1998), *Proposed Rule for Disposal of High Level Radioactive Waste at a Proposed Geological Repository at Yucca Mountain*, Nevada, 10 CFR Part 63, US Nuclear Regulatory Commission.

US NRC (2001), *Part 63 – Disposal of High-Level Radioactive Wastes in a Geological Repository at Yucca Mountain, Nevada*, Code of Federal Regulations, Title 10, Part 63, Washington, D.C., United States, www.nrc.gov/reading-rm/doc-collections/cfr/part063/.

US NRC (2003), *Yucca Mountain Review Plan*, NUREG-1804, Final Rev. 2, US Nuclear Regulatory Commission, www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1804/

US NRC (2005), 10 CFR *Part 63, Implementation of a Dose Standard after 10 000 Years, Proposed Rule*, Federal Register 70:173, pp. 53313-53320, US Nuclear Regulatory Commission, Washington D.C., United States

Vieno, T., Lieikoinen, J., Löfman, J. Nordman, H. & Mészáros, F. (2003), *Assessment of disturbances caused by construction and operation of ONKALO*. Posiva report 2003-06.

Appendix 1

THE QUESTIONNAIRE

1. Context

1.1 Give the name of the organisation on whose behalf the responses are being provided and the main role of this organisation.

1.2 Describe briefly the status of your national programme.

1.3 Describe briefly the disposal system or systems to which your responses relate.

2. Time frames (general)

2.1 What timescales or time frames are mentioned in your national regulations?

2.2 What factors do or should determine the overall period addressed by a safety assessment or safety case?

2.3 Is it valuable or necessary to divide the overall period addressed by a safety assessment or safety case into a number of shorter periods ("time frames"), either in carrying out the assessment or in presenting the findings to different audiences? If so, why, and on what basis can or should time frames be defined.

3. Evolving role of the system components

3.1 What guidelines, requirements or principles related to stability or durability of system components (including both the engineered system and the geosphere) have been defined, either by the regulator or the implementer, for the design and siting of a disposal system? What is the basis for these guidelines, requirements or principles?

3.2 The mechanisms by which a disposal system provides safety may vary with time. Is this true of systems considered by your national programme and, if so, give examples based on one system that explain how (if the disposal system evolves as expected) different components contribute to safety as a function of time.

4. Geosphere stability

4.1 Taking an example from your national programme, what events and processes affect how the safety role of the geosphere changes over time?

4.2 Again taking an example from your national programme, is there a limit to how long the geosphere can be relied upon to play some role in a safety case and, if so, what uncertainties or other factors determine this limit?

5. The influence of the pre-closure phase and period of institutional control on long-term safety and its assessment

5.1 Taking the example of a disposal system analysed by your national programme and considering the impact of the pre-closure phase:

a) Do any processes initiated prior to repository closure influence time frames in the post-closure period?

b) Are these time frames dependent on the duration of the pre-closure phase and how is this dependence treated in post-closure safety assessment?

5.2 Again taking the example of a disposal system analysed by your national programme and considering institutional control in the post-closure phase:

a) Is a period of post-closure institutional control foreseen and if so what sets the duration of this period?

b) How can a period of post-closure institutional control affect long-term safety and its assessment?

6. FEPs and scenarios

6.1 Taking the example of a safety assessment or safety case from your national programme:

a) What are the characteristic timescales of the key processes defining the expected evolution and performance of the system?

b) Is there a link between these timescales and the division of the post-closure period into time frames (as defined in 2.3)?

6.2 Again taking the example of a safety assessment or safety case from your national programme (or based on your national regulations):

a) What uncertainties or perturbing phenomena, have (or should) be considered that lead to alternative scenarios or deviations from the expected path of evolution, and to what extent are these specified by regulations?

b) Can the deviations occur at any time, or are they of relevance only over certain time frames and, if the latter, what determines these time frames?

c) For the specific case of human intrusion, over what period must the possibility of such an event be considered, and why?

7. Modelling approaches

7.1 Do you apply (or recommend/require the application of) different modelling approaches when analysing system performance in different time frames and, if so, explain why, giving examples of the different approaches that can be used and how they are justified?

7.2 Are (or should) regulators (be) more stringent in their requirements on the justification of model assumptions in some time frames compared to others? If possible, give practical examples of how temporal limits to the reliability or applicability of models have been established.

7.3 What is your approach to (or recommendations/requirements on) the treatment of transient processes occurring at different times and extending over different timescales? Give examples of any transient properties of the system that are incorporated explicitly in safety assessment models. Is there a need for further development in this area?

7.4 Do "stylised approaches" have a role in areas other than human intrusion and biosphere, such as long-term evolution of the geosphere at very long times?

8. Uncertainty management

8.1 What are the regulatory requirements for the treatment of uncertainties in safety assessment in order to show that a system complies with regulatory standards, and do these requirements vary as a function of the time under consideration?

8.2 Taking the example of a disposal system analysed by your national programme:

a) What are the main uncertainties affecting the performance of each major system component as a function of time or in different time frames, how are these uncertainties treated in safety assessment, and does this treatment change as a function of time?

b) What impact (if any) do these uncertainties have on the overall safety provided by the system? If possible, provide illustrations of how the chosen site and design can mitigate the effects of uncertainties.

9. Safety indicators and the development of arguments for safety

9.1 When analysing the radiological consequences of different scenarios:

a) Are certain safety indicators most appropriate or more emphasised in particular time frames, what factors determine the start points and end points of these time frames and what safety indicators or safety arguments, if any, are appropriate beyond the period when the evolution of the geological environment can be predicted with confidence?

b) With what measures or protection criteria are or should the safety indicators be compared, and how are they derived?

9.2 Taking the example of a disposal system analysed by your national programme, is there an initial period when no release from parts of the system or the system as a whole is expected and, if so, what justifications are given for the no release period?

9.3 In practice, have natural analogues contributed significantly to the understanding of slow processes operating over long timescales and is there a justification for more widespread use of such analogues?

10. Developing and presenting the safety case

10.1 Are (or should) issues associated with timescales (be) addressed explicitly, e.g. in a dedicated section of a safety report? If yes, please explain how; if no, please explain why.

10.2 Is (or should) more emphasis (be) placed on some time frames and less on others:

a) when presenting a safety report, e.g. for regulatory review, and

b) when presenting a safety case or the findings of a safety assessment to a wider, non-specialist audience?

10.3 What is the view of your organisation on the need for further development or regulatory guidance on the presentation and communication of the results of safety assessments in different time frames and what form should the guidance take?

11. Supporting documentation

11.1 Please provide a primary reference and, if necessary, a small number of additional references that support your responses to this questionnaire

Appendix 2

Acronyms

AkEnd	Arbeitskreis Auswahlverfahren Endlagerstandorte, Germany
Andra	National Agency for Radioactive Waste Management, France
AVN	Association Vinçotte Nuclear, Belgium
BCF	Boda Claystone Formation
BfS	Bundesamt für Strahlenschutz, Germany
CFR	Code of Federal Regulations
CSNF	Commercial Spent Nuclear Fuel
CoRWM	Committee on Radioactive Waste Management, United Kingdom
DGSNR	Direction Générale de la Sûreté Nucléaire et de la Radioprotection, France
EIS	Environmental Impact Statement
ENRESA	Empresa Nacional de Residuos Radiactivos, S.A, Spain
ERAM	Endlager für Radioaktive Abfälle Morsleben, Germany
FEPs	Features, Events, Processes
GRS	Gesellschaft für Anlagen und Reaktorsicherheit, Germany
HGS	Hungarian Geological Survey
IAEA	International Atomic Energy Agency, Vienna, Austria
ICRP	International Commission for Radiological Protection
IGSC	Integration Group for the Safety Case of the OECD/NEA
IRSN	French Institute for Radiological Protection and Nuclear Safety
JNC	Japan Nuclear Cycle Development Institute
KBS-3	*Kärnbränslesäkerhet*, Nuclear Fuel Safety
LTSC	Long-term Safety Criteria
Nagra	National Cooperative for the Disposal of Radioactive Waste, Switzerland
NEA	Nuclear Energy Agency
NF	Near Field
Nirex	United Kingdom Nirex Limited
NISA	Nuclear and Industrial Safety Agency, Japan
NPP	Nuclear Power Plant
NSC	Nuclear Safety Commission in Japan
NUMO	Nuclear Waste Management Organisation of Japan
NWMO	Nuclear Waste Management Organisation, Canada
OECD	Organisation for Economic Co-operation and Development
ONDRAF/NIRAS	National Organization for Radioactive Waste and Fissile Materials, Belgium
OPC	Ordinary Portland Cement
OPG	Ontario Power Generation, Canada
ORD	Office of Repository Development
PURAM	Public Agency for Radioactive Waste Management, Hungary
QA	Quality Assurance
RAWRA	Radioactive Waste Repository Authority, Czech Republic
RWMC	Radioactive Waste Management Committee

SAFIR 2	Safety Assessment and Feasibility Interim Report
SAM Ltd	Safety Assessment Management Ltd
SCK•CEN	Nuclear Energy Research Center, Belgium
SKB	Swedish Nuclear Fuel and Waste Management Co
SKI	Swedish Nuclear Power Inspectorate
SPIN	European Commission Research Project on Testing of Safety and Performance Indicators
SSI	Swedish Radiation Protection Authority
STUK	Radiation and Nuclear Safety Authority, Finland
THMC	Thermal, Hydraulic, Mechanical, Chemical
URL	Underground Research (or Rock) Laboratory
US DOE-YM	US Department of Energy, Yucca Mountain
US EPA	US Environmental Protection Agency
US NAS	US National Academy of Science
US NRC	US Nuclear Regulatory Commission
WIPP	Waste Isolation Pilot Plant, United States

Appendix 3

CONTEXT FOR THE RESPONSES

This appendix gives the national and programmatic context on the basis of which the various participating organisations responded to the questionnaire (see Question 1). Programme status refers, in general, to the situation in the spring of 2005, which was the deadline for responses to the questionnaire, although more recent developments have, in some cases, also been included.

Belgium

Organisations responding to the questionnaire

Responses from Belgian organisations were received from AVN and jointly from ONDRAF/NIRAS and SCK•CEN.

AVN – the Association Vinçotte Nuclear – is an authorised inspection organisation licensed by the Federal Agency for Nuclear Control to carry out the surveillance of the Belgian nuclear installations in the framework of the Belgian laws and regulations. It is through the association of the FANC on one side, and the control organisations such as AVN on the other, that the function of regulator as stipulated in article 20, 1st paragraph, of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management, is ensured.

ONDRAF/NIRAS – the Belgian Agency for Radioactive Waste and Enriched Fissile Material – is legally in charge of the management of all radioactive waste on Belgian territory. In this framework, ONDRAF/NIRAS is responsible for the R&D programme related to the geological disposal of high-level and long-lived waste.

SCK•CEN – the Nuclear Energy Research Centre – is the main R&D subcontractor of ONDRAF/NIRAS for the deep disposal programme, and assisted ONDRAF/NIRAS in providing responses.

Programme status

With the publication of SAFIR 2 (Safety Assessment and Feasibility Interim Report) in 2002 ONDRAF/NIRAS ended the second methodological R&D phase of the deep disposal programme for high-level and long-lived waste. Since 2004, the programme entered the third methodological R&D phase. The prime aim of these methodological phases is to establish if it is feasible, technically and financially, to design, build, operate and close a safe deep repository for this waste on Belgian territory, without prejudging the actual disposal site. The reference formation and site for methodological research is the Boom Clay at Mol/Dessel, which has been extensively studied from the surface and underground. Belgium has benefited from the HADES URL at Mol-Dessel, which was established at the beginning of the 80s, soon after the inception of the programme.

Repository concepts

Belgian responses to the questionnaire were based on the current concept of disposal of vitrified waste from reprocessing, spent fuel and some intermediate-level waste forms in an approximately 100 m thick Boom Clay layer at a depth of between about 190 m and 290 m. The upper- and underlying-geological formations are sandy water bearing sediments. The engineered barrier design for vitrified high-level waste and spent fuel has been extensively reviewed and modified since the SAFIR 2 report. In the current design, the different components of the engineered barriers (waste, overpack, buffer material and stainless steel envelope) will be assembled at the surface inside supercontainers, before being transported to underground disposal galleries. The galleries for high-level waste and spent fuel have typical diameters of 2 to 2.5 m, and are lined with concrete wedge blocks to stabilise the excavated galleries against clay convergence. Access to the disposal galleries is through a series of shafts and an access gallery. The reference materials for the overpack, the buffer and the container lining are respectively carbon steel, OPC cement based concrete and stainless steel. Galleries are backfilled with a cement-based material.

Canada

Organisations responding to the questionnaire

Responses were received from OPG – Ontario Power Generation – the implementing organisation charged with the disposal of Canadian low- and intermediate-level waste. OPG is also implementing used fuel storage, but it is anticipated that the Canadian Nuclear Waste Management Organization (NWMO) will eventually become the implementing organisation for long-term management of used fuel.

Programme status

A candidate host site has been identified for a repository for low- and intermediate-level waste in the deep sedimentary rock under the Bruce nuclear site. In February 2005, the community indicated its support for the proposal. OPG is currently in the early stages of planning for site characterisation and environmental assessment.

NWMO is evaluating options for long-term management of used fuel in Canada. A recommendation is to be submitted to the federal government in late 2005. Subsequently the federal government will decide on the approach.

Repository concepts

Canadian responses to the questionnaire were based on the proposed low- and intermediate-level waste repository. The wastes include non-processible waste (such as metal scraps), compacted soft wastes, incinerator ashes, resins, activated components and decommissioning wastes. The geological environment at the proposed site is sedimentary rock at a depth of approximately 660 m. The repository will be located in either limestone or shale rock. The waste packages will be placed in vaults excavated in the rock. The vaults will be sealed but not backfilled. The shafts will eventually be filled and sealed.

Czech Republic

Organisations responding to the questionnaire

Responses were received from RAWRA – the Czech Radioactive Waste Repository Authority – the organisation responsible for radioactive waste disposal and research and development activities connected to waste disposal, including geological repository development.

Programme status

The Czech national programme is in the process of selecting a site for detailed characterisation. Currently there are six candidate sites, chosen on the basis of air-born geophysical measurements, remote sensing, field checking, and pre-feasibility studies.

Repository concepts

Czech responses to the questionnaire were based on disposal of spent fuel and other long-lived wastes in long-lived containers (probably including steel canisters) surrounded by a (probably clay-based) buffer in disposal areas mined in a granite formation.

Finland

Organisations responding to the questionnaire

Responses were received from STUK, the Radiation and Nuclear Safety Authority of Finland. STUK is the Finnish regulatory body.

Programme status

In the Finnish programme, the first (political) authorisation step, the decision in principle for a repository for spent fuel disposal, was taken in 2001, allowing the selection of the disposal site (Olkiluoto). An underground rock characterisation facility is currently being excavated. In 2012, it is foreseen that the application for a construction licence will be submitted. If the application is accepted, the operation of the facility is currently foreseen as beginning in 2020.

Repository concepts

Finnish responses to the questionnaire were based on disposal according to the KBS-3 concept (see Sweden, below).

France

Organisations responding to the questionnaire

Responses from French organisations were received from Andra and IRSN.

Andra is the French National Agency for the management of radioactive waste. Andra designs and implements disposal solutions suited to each category of waste. It manages, operates and monitors surface-disposal for low-level radioactive waste, and is in charge of implementing management solutions for other wastes.

IRSN provides technical support to the French Safety Authority in charge of underground repository safety assessment for high level wastes.

All responses to the questionnaire from these French organisations refer (except when noted) to the geological disposal project for the management of intermediate level waste (such as bituminous waste, cementeous waste, and metallic waste), vitrified waste and spent fuel. The potential of clay host rock is currently under consideration.

Programme status

Studies related to the geological disposal in France are at the feasibility stage. They rely, in the case of studies on clay formations, on data from a site-specific underground rock laboratory (the Bure URL) located at the Meuse/Haute-Marne site in the Eastern part of the Paris Basin and are documented in "Dossier 2005 Argile". Studies on granite are based on generic data and are documented in "Dossier 2005 Granite".

Repository concepts

French responses to the questionnaire were mostly based on the concept studied at the Bure URL. In this concept, the repository is constructed at 500 m depth in the 150 million year old Callovo Oxfordian indurated clay (argillite), which has surrounding clay and limestone formations. Specific repository modules are dedicated to each waste type. Intermediate-level waste is placed in concrete-overpacks in concrete-backfilled cavities. Vitrified high-level waste is placed in horizontal tunnels inside steel overpacks designed to isolate the waste from water until the temperature has sufficiently decreased. In the case of spent fuel, which is placed in horizontal tunnels inside steel overpacks with a surrounding bentonite buffer, the design lifetime of the overpacks is around ten thousand years, with up to four fuel rods in each overpack. The repository is designed so to facilitate reversibility.

Germany

Organisations responding to the questionnaire

Responses from German organisations were received from BfS, GRS-B and GRS-K.

BfS is the Federal Office for Radiation Protection. The German Atomic Energy Act gives the responsibility for the disposal of radioactive waste to the federal government, with BfS as the responsible authority (implementer).

GRS is an independent and non-profit scientific-technical expert and research organisation in the field of nuclear reactor safety and the entire nuclear fuel cycle. The main task of the Final Repository Safety Research Division of GRS/Brunswick (GRS-B) is the development of safety assessment methodologies for repositories for radioactive waste. On behalf of BfS, GRS-B has performed the safety analyses for the post-closure phase of the Morsleben repository. The Waste Management Division of GRS/Cologne (GRS-K) provides technical expertise to the German regulator BMU (the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) and to licensing authorities (state governments).

Programme status

In Germany, it is intended to dispose of all types of radioactive waste in deep geological formations. Prior to 1980 the former iron ore mine Konrad was selected as a site for disposal of short-lived and long-lived radioactive waste with negligible heat generation and the salt dome at Gorleben as a site for the disposal of all types of solid and solidified radioactive waste, including heat generating radioactive waste originating from reprocessing and spent fuel elements. Both sites are in the Federal State of Lower Saxony. In the former German Democratic Republic, short-lived low- and intermediate-level radioactive waste was disposed of in the Morsleben (ERAM) repository, a former rock salt and potash mine.

The Lower Saxony administrative court decided on 8 March 2006 that the permission given for the Konrad repository was justified. At Gorleben, a moratorium on underground exploration became effective in 2000, and will remain in force for at most 10 years, pending clarification of conceptual and safety related issues. The ERAM repository began operation in 1971, and the disposal phase came to an end in 1998. A licence application for the closure of the repository is being prepared by BfS, who became the responsible operator of the repository after the reunification of Germany in 1990.

The German radioactive waste management and disposal concept is currently being reviewed, and further sites in various host rocks shall be investigated for their suitability. Thus, the Federal Minister for the Environment, Nature Conservation and Reactor Safety (BMU) set up an interdisciplinary expert group (AkEnd) to develop repository site selection criteria and respective procedures on a scientifically sound basis. AkEnd finished its work at the end of 2002 (AkEnd, 2002).

Repository concepts

German responses to the questionnaire relate to (i), the Konrad iron ore mine, (ii), the ERAM repository and (iii), a generic repository for spent fuel and high-level waste in a salt dome. In the case of Konrad, responses do not refer to any technical design or construction details but only to experiences with regard to acceptance questions obtained during the licensing procedure, including a public hearing. In the case of ERAM, many open cavities exist in this former mine with dimensions of up to 140 m in length, 40 m in width and in height. A few of these cavities located on the outskirts of the mine have been used as waste disposal areas, and will be sealed from the remaining inner parts of the mine. All openings will be backfilled to preserve the integrity of the salt barrier. The generic repository is based on an earlier German concept that envisaged the direct disposal of spent fuel rods in self-shielding POLLUX casks in drifts, and the disposal of vitrified high active waste in smaller canisters placed in boreholes. Subsequently the drifts and boreholes would be backfilled with crushed salt. Other engineered barriers in the reference concept were dams for drift sealing, borehole plugs and shaft sealing.

Hungary

Organisations responding to the questionnaire

A joint response from several Hungarian organisations was received.

PURAM – the Public Agency for Radioactive Waste Management – which was established to deal with multilevel tasks associated with the disposal of radioactive waste, interim storage and final disposal of the spent fuel, as well as with the decommissioning of nuclear facilities in Hungary.

HGS – the Hungarian Geological Survey – an independent specialised authority under the supervision of the Ministry of Transport and Economy. Exploration plans and final reports are to be submitted to and licensed by the HGS. In other licensing procedures the HGS is involved as a specialised authority, which means that its consent is a prerequisite of the final licence.

NRIRR – the Frederic Joliot-Curie National Research Institute for Radiobiology and Radiohygiene – which is the professional centre for radiation hygiene and radiation protection in Hungary. NRIRR performs the licensing and controlling of siting, construction, commissioning, operation, modification and closure of a radioactive waste disposal facility.

ETV-ERŐTERV – Spent Fuel and Radioactive Waste Management – which is an independent engineering company working on the fields of conventional and nuclear engineering.

Golder Associates (Hungary) Ltd., which is an independent engineering company working on the fields of hydrology and safety and environmental impact assessments of radioactive waste facilities.

HAEA – the Hungarian Atomic Energy Authority – which is an administrative body with national jurisdiction directed by the Government, with independent duties and regulatory responsibilities in matters related to the peaceful use of atomic energy.

Programme status

A repository is foreseen for low- and intermediate-level waste from the Paks Nuclear power plant, which would be constructed on the outskirts of Bátaapáti village (in the Üveghuta area) at a depth of 200-250 m below the surface, at 0-50 m above sea level in granite of Lower Carboniferous age. The exact location of the disposal area will be defined after additional geological investigations. Design of the layout and of the characteristics of the disposal areas will need to be refined after further geological investigations.

Geological disposal of spent fuel, high-level waste and long-lived intermediate-level waste is also foreseen. Between 1995 and 1998 a short-term programme (STP) was launched to characterise the rock mass known as the Boda Claystone Formation (BCF). The studies, which utilised an exiting mine, concluded that the rock was potentially suitable for disposal of spent fuel and high-level waste. In 2000, a nationwide site screening study was carried out, which identified 32 lithological formations potentially suitable for a deep geological repository. In 2004, surface-based investigations restarted in the Boda area, the aim of which is to identify by 2008 a location for an underground research laboratory for more detailed investigations of the site.

Repository concepts

Hungarian responses to the questionnaire relate to a repository for high-level waste and long-lived intermediate-level waste in the BCF, at an appropriate depth and location yet to be specified.

Japan

Organisations responding to the questionnaire

A response from Japanese organisations was received jointly from JNC and NUMO.

JNC, the Japan Nuclear Cycle Development Institute, is legally in charge of research and development related to the geological disposal of vitrified high-level radioactive waste, and provides a scientific and technical information base to support both the implementing organisation – NUMO, and the regulatory bodies – the Nuclear Safety Commission (NSC) and the Nuclear and Industrial Safety Agency (NISA).

NUMO, the Nuclear Waste Management Organisation of Japan, is legally in charge of implementation, including repository site selection, developing relevant licence applications and construction, operation and closure of a repository for the geological disposal of vitrified high-level waste from the reprocessing of spent nuclear fuel.

Programme status

The Japanese programme for geological disposal of high-level waste has moved from feasibility studies to an implementing phase. As laid down in Japanese law, the siting process will consist of three steps. Firstly, Preliminary Investigation Areas (PIAs) for potential candidate sites will be nominated based on site-specific literature surveys focusing on long-term stability of the geological environment. Secondly, Detailed Investigation Area(s) (DIAs) for candidate site(s) will be selected from the PIAs following surface-based investigations, including boreholes, carried out to evaluate the characteristics of the geological environment. Thirdly, detailed site characterisation, including underground research facilities, will lead to selection of the site for repository construction. In 2002, NUMO announced the start of open solicitation of volunteer municipalities for PIAs with publication of an information package and has been at the first stage of the siting process since that time. According to the present schedule, repository operation may start as early as the mid-2030s.

Repository concepts

Japanese responses to the questionnaire were based on a reference engineered barrier system in which the vitrified high-level waste encapsulated in steel overpacks is emplaced in disposal tunnels or pits with surrounding compacted bentonite/sand buffer. A range of siting environments for repository construction would be possible depending on the volunteer sites. They could have different characteristics, including, for example, inland and coastal areas (geographic aspects), mountainous, hilly and plain areas (topographic aspects) and areas with crystalline or sedimentary rocks (geological aspects). The underground facilities will be constructed in stable rock formations at least 300 m below the surface in accordance with Japanese legal requirements.

Spain

Organisations responding to the questionnaire

Responses were received from Enresa, which is the Spanish implementing organisation responsible for the management of radioactive wastes.

Programme status

The Spanish high-level waste management programme is at the stage of generic feasibility studies. Preliminary studies for identification of favourable host formations have been carried out in the past, but no active programme of site selection is in progress at present.

Repository concepts

Spanish responses to the questionnaire were based on conceptual designs for spent fuel repositories in salt, clay, and granite. Safety assessment exercises for repositories in granite and clay have been carried out (two iterations per host rock). The most recent exercises are ENRESA 2000 (granite) and ENRESA 2003 (clay).

Sweden

Organisations responding to the questionnaire

Responses from Swedish organisations were received from SKB and jointly from SKI and SSI.

SKB – the Swedish Nuclear Fuel and Waste Management Company – is the implementing organisation in Sweden.

SKI – the Swedish Nuclear Power Inspectorate –which is charged with (i), the supervision of the nuclear industry programme for development of a system for deep geological disposal of spent nuclear fuel and long-lived nuclear wastes, (ii), review of licence applications and providing comments to the government as a basis for its decisions, (iii), supervision of the construction, commissioning, operation and decommissioning of facilities, and (iv), supervision of the closure of repositories.

SSI – the Swedish Radiation Protection Authority – which, in the context of radioactive waste disposal, is charged with (i), regulation and supervision of occupational radiological health, (ii), defining the standard and promulgation of guidance for post-closure risk and environmental protection, and (iii), supervision in relation to the above regulatory activities.

Both SKI and SSI take part in the dialogue between stakeholders as a preparation for the licensing procedure for facilities, most notably an encapsulation plant and a repository for spent fuel.

Programme status

The two principal tasks in the Swedish programme are to locate, build and operate (i), a geological repository for spent nuclear fuel and (ii), an encapsulation plant in which the spent fuel will be placed in canisters before being emplaced in the repository.

SKB is currently pursuing site investigations for a geological repository for spent nuclear fuel at two potential locations in the municipalities of Östhammar and Oskarshamn. The aim is to build a deep repository at one of these candidate sites, provided that the bedrock and other relevant conditions are found suitable. Moreover, the detailed basis for construction of spent fuel canisters is being developed.

In November 2006, an application to build the encapsulation plant will be made. At the end of 2009, according to current (autumn 2006) plans, the application for final siting and construction of a repository will be made

Repository concepts

Swedish responses to the questionnaire were based on disposal according to the KBS-3 concept. The concept involves encapsulation of spent fuel elements in corrosion resistant copper canisters with inserts of iron for handling of mechanical loads. The canisters are emplaced in a mined repository at a depth of about 500 m in saturated crystalline rock, and surrounded by a buffer of compacted bentonite clay. The most detailed plans consider a vertical emplacement of canisters, but horizontal emplacement is also considered a feasible option.

Switzerland

Organisations responding to the questionnaire

Responses were received from Nagra, the Swiss National Cooperative for the Disposal of Radioactive Waste, which is responsible for developing geological repositories for the safe disposal of all categories of radioactive waste. This includes the preparation of the necessary scientific and technical basis.

Programme status

Two types of repositories are foreseen in Switzerland: (i) a repository for the disposal of spent fuel, vitrified high-level waste and long-lived intermediate-level waste and (ii) a repository for the disposal of low- and intermediate-level waste arising from the operation and decommissioning of Swiss nuclear power plants and from medicine, industry and research.

Within the spent fuel, vitrified high-level waste and long-lived intermediate-level repository programme, Project *Entsorgungsnachweis* ("Disposal Feasibility") was submitted to the Federal Government at the end of 2002 for review. This project has the aim to demonstrate that a safe repository can be implemented and that a corresponding site exists within Switzerland. The review of the project by the Swiss authorities, which came to positive conclusions, was completed in August 2005, and was followed by a broad, three-month public consultation phase. No additional technical issues (compared with the authorities review findings) were identified in the public consultation phase. Based on the results of the review and the public consultation phase, the Swiss Government (the Federal Council) concluded on 28 June 2006 that disposal feasibility of SF/HLW/ILW in Switzerland had been successfully demonstrated.

In the case of low- and intermediate-level waste (L/ILW) programme, a repository project at Wellenberg, Canton of Nidwalden, had to be abandoned on political grounds after the population of the Canton of Nidwalden rejected the plans for the proposed underground investigations in 2002.

For both the HLW and the L/ILW programmes, the next stage will focus on the definition and implementation of a site selection process. As a first step in the siting process the Federal Office of Energy is currently preparing a document defining a site selection procedure along with the corresponding criteria. It is expected that the Swiss Government will approve this site selection procedure in 2007 after a period of broad consultation with the cantons, the neighbouring countries and different interest groups. The siting process will allow extensive public participation.

Repository concepts

Swiss responses to the questionnaire relate to the repository for spent fuel, vitrified high-level waste and long-lived intermediate-level wastes analysed in Project Entsorgungsnachweis. The host rock is the Opalinus Clay in the Zürcher Weinland in northern Switzerland. This is an over-consolidated clay stone of Middle Jurassic age. In the investigation area, the clay forms a layer about 100 m thick and is embedded in the so-called confining units, with properties similar to the Opalinus Clay and with thicknesses of about 100 m above and about 160 m below the host rock. The proposed repository would be constructed at about 650 m below surface. Steel canisters containing either spent fuel or high-level waste would be emplaced coaxially within a system of parallel tunnels constructed in the centre of the formation. The tunnels would be backfilled with compacted bentonite. Intermediate-level waste would be emplaced in larger-diameter tunnels, backfilled with a cementitious mortar. Access to the system of tunnels would be provided, during construction and operation, by a spiral ramp. A vertical construction/ventilation shaft is also foreseen.

United Kingdom

Organisations responding to the questionnaire

Responses were received from Nirex – the organisation responsible for supporting UK Government policy by developing and advising on safe, environmentally sound, and publicly acceptable options for the long-term management of radioactive materials in the United Kingdom, i.e. Nirex is an implementing organisation.

Programme status

In the United Kingdom there has been a period of consultation regarding the options for long-term radioactive waste management, undertaken on behalf of Government by an independent Committee on Radioactive Waste Management (CoRWM). CoRWM has recently published its report in which it recommends deep geological disposal as the preferred option for the long-term management of radioactive wastes. However, a site for such a repository has yet to be identified and current safety assessments are therefore undertaken on a generic basis.

Repository concepts

In order to be able to continue to provide advice on the conditioning and packaging of wastes to waste producers, Nirex has developed a generic phased geological repository concept for the disposal of intermediate-level waste and some low-level waste, which provides the basis for the questionnaire responses. In this concept, the waste would typically be grouted into steel drums or concrete boxes and placed in vaults excavated at several hundred metres depth in a geological environment. At a time determined by future generations, the vaults would be backfilled with the cement-based Nirex Reference Vault Backfill and the shafts and access-ways sealed.

United States

Organisations responding to the questionnaire

Responses from United States organisations were received from the US DOE, US EPA and US NRC.

US DOE – the United States Department of Energy – manages the Yucca Mountain Project for the geological disposal of spent-fuel and high-level waste through its Office of Repository Development (ORD). The main role of the ORD is to develop and obtain a licence for Yucca Mountain and to build and operate a repository at Yucca Mountain if the US NRC grants a licence to do so. The US DOE also is the developer, owner, and licensee for the Waste Isolation Pilot Plant (WIPP) deep geological repository for disposal of long-lived transuranic (intermediate level) radioactive waste in New Mexico.

US EPA – the United States Environmental Protection Agency – through its Office of Radiation and Indoor Air (ORIA), Radiation Protection Division (RPD) (i), establishes public health and environmental radiation protection standards for land disposal of spent nuclear fuel, high-level waste, and transuranic radioactive waste and (ii), serves as the "certifying" (licensing) authority and oversees continuing operation of WIPP, a repository for disposal of WIPP.

US NRC – the United States Nuclear Regulatory Commission – is responsible for reviewing a licence application for a potential high-level waste geological repository (submitted by the US DOE) and making a safety decision according to regulations at Code of Federal Regulations, Title 10, Part 63 (10 CFR Part 63). If the US DOE is granted a licence, US NRC will oversee the development of the repository (e.g., subject to US NRC inspection and enforcement of its regulations).

Programme status

WIPP opened in 1999 and has received more than 3 400 shipments from eight sites. It is expected to operate for roughly 30 more years.

In 1993, the US EPA issued its final generic standards for land disposal of spent nuclear fuel, high-level waste and transuranic waste (Code of Federal Regulations, Title 40, Part 191 (40 CFR Part 191)). These standards apply to operation of the WIPP. As the approving regulatory authority, the US EPA also issued compliance criteria to interpret and implement the generic Part 191 standards at WIPP (40 CFR Part 194). In May 1998, US EPA approved the US DOE's certification application for the WIPP. In March 1999, the first shipments of trans-uranic waste to the WIPP took place. US DOE must apply for re-certification every five years, and submitted its application in March 2004. The US EPA is currently in the process of reviewing the re-certification application and expects to make a final decision in early 2006.

The Energy Policy Act of 1992 directed the US EPA to develop site-specific standards for the proposed repository at Yucca Mountain, Nevada (the Waste Isolation Pilot Plant Withdrawal Act of 1992 exempted Yucca Mountain from US EPA's Part 191 standards). The US EPA issued its standards (40 CFR Part 197) in 2001. A legal challenge to the time of compliance resulted in the standards being vacated and remanded to the US EPA for revision. The US EPA is currently in the process of revising its standards.

In 2002, the U.S. Congress and President accepted the recommendation from the Secretary of Energy and designated the Yucca Mountain Site in Nevada for development. The first step in that development is to submit a Licence Application to the U.S. Nuclear Regulatory Commission. The US DOE is in the process of preparing a licence application for a potential repository at Yucca Mountain, Nevada. That licence application is under continued development as the US EPA completes changes to its safety standards and is planned to be submitted as soon as practicable, but no firm date has yet been announced. The Nuclear Regulatory Commission (US NRC) is in the process of modifying its licensing regulations at 10 CFR Part 63 consistent with changes in US EPA's revised standards in 40 CFR Part 197. US DOE's license application must address the modified 10 CFR Part 63, which regulation incorporates the revised 40 CFR Part 197 standard.

Repository concepts

US responses to the questionnaire concerning the Yucca Mountain repository concept describe Yucca Mountain as a desert ridge of layered ash-flow and ash-fall volcanic tuffs, deposited more than approximately 10 million years ago. The thick rock sequence allows the emplacement of waste about halfway between the surface and the water table, which lies about 600 m below the mountain crest. The site is relatively isolated and sits in a closed hydrologic basin, so no radionuclide releases via the groundwater pathway will reach rivers or oceans, or major population centres. Three primary types of waste will be emplaced at Yucca Mountain: (1) spent nuclear fuel rods from all commercial nuclear reactors in the US, (2) vitrified high-level waste glass owned by the US DOE and mainly derived from weapons production, and (3) spent nuclear fuel from US DOE and other government owned or sponsored reactors. The waste is contained in highly durable waste packages made from a nickel-chromium-molybdenum alloy (Alloy 22), and are to be emplaced horizontally in drifts. Titanium drip shields protect the waste packages from potentially corrosive dripping water and falling rocks.

WIPP is located in a relatively flat, arid region. The host rock consists of Permian salt beds formed about 250 million years ago, suggesting long-term geological stability. The primary salt formation is about 2 000 feet thick, beginning 260 metres (850 feet) below the surface. Project facilities include excavated rooms about 650 metres (2 150 feet) below the surface. Ground water below the salt layer is saline and non-potable. WIPP handles materials contaminated with transuranic isotopes during atomic energy defence activities, such as cleaning rags and other contaminated refuse, equipment, tools, protective gear, and sludge. Contact-handled waste does not require special packaging and is placed in excavated rooms (panels). Remote-handled waste will be placed in boreholes in the salt layer between the larger rooms. Over time, it is expected that the salt will encapsulate the waste and provide natural sealing and shielding.

Appendix 4

OBSERVATIONS FROM THE RESPONSES

This appendix gives observations made on the basis of the responses to Questions 2-10. For simplicity, the different respondents are identified either by organisation acronyms or country (see Appendix 2 for a list of acronyms). These observations have been reviewed by the participating organisations to ensure that they properly reflect these organisations' views. It should be noted, however, that attributing an observation or view to a particular organisation does not necessarily mean that this is the only organisation that subscribes to this view.

Questionnaire Section 2: Time frames (general)

Timescales and time frames mentioned in national regulations (Question 2.1)

- In the United States, a distinction was drawn between the time frame for safety assessment calculations to be presented in an Environmental Impact Statement and the time frame for compliance. US regulations for Yucca Mountain (now vacated and remanded to US EPA for revision – see Appendix 3) required calculations to the time of maximum consequences (but within the period of geological stability, which is considered to be 10^6 years, in accordance with the recommendations of the US NAS, but compliance with quantitative licensing criteria was required for a 10^4 year time frame. Beyond 10^4 years, calculations inform society – but the regulations recognised that significant uncertainties lead to considering them as more qualitative indicators of performance. The US 10^4-year compliance period is also applied at WIPP, as specified in the regulatory requirements for WIPP published as Title 40, Code of Federal Regulations, Parts 191 and 194.
- SKI regulations give 104 years as the minimum time covered by safety analysis, but also state that analyses should continue as long as barrier functions are required. According to Swedish (SSI) guidance, however, no account need be given of the period > 106 years, even if peak consequences are indicated to occur thereafter and there is still the potential for causing harmful effects.
- The French safety rule, which sets guidelines for safety assessments of geological disposal, mentions various time frames, including institutional surveillance, rock stability, radioactivity decrease, glaciation and time frames characterising the natural evolution of the system.
- Swiss regulations mention (for spent fuel and high-level waste) an initial period of high heat output from the waste and high radiological toxicity, both of which decrease over time due to radioactive decay.
- From the various answers, the following Table A4.1 gives an overview of regulatory statements on the various time frames with related criteria.

Table A4.1: **Statements on time frames in national regulations**

Time frame	Regulatory statements
Time frames related to radioactive decay	
0 – a few hundred to 10^3 years	Initial period of high heat output, activity, etc for spent fuel/high-level waste – complete containment during a period of about a thousand years should be aimed at according to regulations.
Time frames related to the general predictability of the engineered repository and its environment	
0 – a few thousand years	Time frame over which, according to on-going discussion on safety regulation in Japan, assessments are likely to be "reliable" (see also Question 7.2). According to Swedish Regulation (SKI), a safety assessment shall cover a time frame during which barrier functions are required, but at least 10^3 years.
0 – ~10^4 years	This is the compliance period specified in current US regulations for the WIPP repository. For the Yucca Mountain repository, the standard is being revised to include the period of peak dose – see Appendix 3 – but the previous dose limit is being retained for the first 10^4 years. According to the French safety rule, it is expected that the stability of the host formation should be demonstrated, and that safety assessments should include explicit uncertainties studies in this period.
0 – 10^5 years	Time frame in which, according to French safety rule, normal evolution is to be taken into account in the "reference situation" supporting the safety assessment – thereafter natural events are part of "random evolution" – meaning that they do not need to be considered as "expected evolution", but rather as perturbations (see Question 6.2).
Time frames related to changes in the surface environment and in human habits	
0 – 10^3 years	The period when, according to Swedish (SSI) regulations, assessment shall be based on quantitative analyses of the impact of the repository on human health and the environment.
0 – several thousand years	"Environmentally predictable future" in Finnish regulations (STUK) during which dose/risk constraints apply – exposures to humans reasonably predictable.
> 10^3 years	According to Swedish Regulations (SSI FS, 1998), the period for which assessment should be based on various scenarios providing "illustrations" of the protective capability of the repository, assuming certain conditions.

Time frame	Regulatory statements
Time frames related primarily to major climate change	
0 – 5 × 10^4 years	According to the French safety rule, the period during which no glaciation is expected or needs to be considered in safety assessment – thereafter glaciation must be taken into account in safety assessment.
0 – 10^5 years	According to Swedish (SKI) guidance, safety analysis should cover expected climate changes in this period, which corresponds to the period of the next complete glacial cycle.
About 10^4 years to a few hundreds of thousands of years	"Era of extreme climate changes" in Finnish regulations – biosphere scenarios highly uncertain – radionuclide-specific flux constraints apply.
> 10^5 years	According to Swedish (SSI) proposed guidance, risk analysis can be based on stylised descriptions of future cycles of major climate changes, and large harmful occurrences such as earthquakes.
Time frames related primarily to long-term changes in the geological environment[1]	
10^4 years	According to guidance in France and Hungary, the minimum period in which host rock stability must be demonstrated and in which safety assessments should consider uncertainties in detail (thereafter, a less detailed approach may be used, with complementary, more qualitative safety arguments).
10^6 years for a well-chosen site – see also Question 4.2	The period over which reliable geoscientific prognoses can be made (German Draft Criteria) – predictability of engineered barriers is decreasing – safety case should increasingly emphasise containment by geosphere. In the US Yucca Mountain repository case, it has been proposed to revise regulations to evaluate safety over this time frame because it represents a period during which geological stability seems assured for this site.
> 10^6 years or from a few hundreds of thousands of years	The time frame over which, according to German Draft Criteria (>10^6 years) and Finnish regulations, only qualitative statements about retention of radionuclides are possible – should test that there are no signs of an abrupt safety-relevant change in the "isolating rock zone" or host rock.

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[1] Hungarian regulations also mention a past time frame – no active faulting in the designated area in the past 10^5 years.

Time frame	Regulatory statements
Time frames related to periods of monitoring and institutional control	
0 – 50 years	Monitoring of the repository and its surroundings is possible and the minimum period of “active institutional control” (monitoring and control and environmental conditions, including concentrations of radioactive isotopes) in Hungarian regulations.
0 – 500 years	According to the French safety rule, the period of time during which “memory” and records of the disposal are maintained, reducing considerably the likelihood of human intrusion. German Draft Criteria do not require consideration of human intrusion in this time frame.

Factors determining the overall period addressed by a safety assessment or safety case (Question 2.2)

(i) General observations on “cut-offs”

- Cut-off time for safety assessment calculations are often a matter for the implementer to decide/justify – regulatory guidance can range from very precise (United States) to very flexible (France, Hungary, Spain).
- Additionally, AVN mentions that the overall periods to be addressed in a safety assessment or a safety case should not be arbitrarily fixed by regulatory documents.
- Some regulations/regulatory guidelines specify that calculations, esp. of dose/risk, must continue at least until the time of peak consequences (Canada, Switzerland, Hungary, Czech Republic, Japan, Sweden and United States).
- Acknowledging that the ability for geoscientific prognoses is limited in time, the German Draft Criteria require that the repository be erected at a site that allows predictions for at least one million years (GRS-K).
- Swedish regulations state 104 years is the minimum period to be covered, but the actual cut-off needs to be justified by an assessment of how long barrier functions are required – which is much longer than 104 years for spent fuel and high-level waste (SKI/SSI).
- Safety assessment calculations are in many cases halted at 106 years (or they are most emphasised in the safety case within this period – i.e. 106 years regarded as a “key milestone”) on the basis of arguments such as that, within this time frame, the radioactivity of the waste will have significantly decreased, the stability of the host rock can be predicted, all transient processes are judged to be complete, transport of the radionuclides that are most important with respect to safety takes place, and peak calculated dose occurs (Andra).
- Calculations are sometimes extended beyond this time, but it is recognised that the results need qualifying statements regarding the reliability of the models used; and in some safety reports, assessment is complemented with a brief discussion on the development after that time period (e.g. SKB, Nagra).
- As examples, Nagra extends calculations to 107 years to add confidence to the 106 years results; dose calculations in SAFIR 2 cut off at 108 years, emphasising the highly illustrative

nature of the calculations beyond 105 years, but in the future will consider an earlier cut-off (ONDRAF/NIRAS response to Question 9.1a).

- ONDRAF/NIRAS engaged in discussion with regulator about the acceptability of this approach.
- AVN points out that a different cut-off may apply when assessing non-radiological hazard.
- AVN also points out that the duration of overall periods for safety assessment and safety case may be re-evaluated if judged appropriate through the licensing process.

(ii) The compliance period and the cut-off time for safety assessment calculations

- Most regulations stipulate criteria for the entire period covered by safety assessment calculations.
- Although not stated in the French safety rule, safety assessment calculations could be performed over a time frame that includes the time of maximum dose, even if this arises after one million years (Andra).
- In some instances, there are different criteria for different timeframes (see also Section 3.1 of main text). For instance, proposed new US regulations for Yucca Mountain (see Appendix 3) apply a different standard to the 104-year compliance period than to the compliance period beyond 104 years.
- The proposed regulation would replace a vacated regulation with a compliance period of 104 years. The proposed standard to be applied beyond 104 years is different because of concerns over the management of uncertainties and the meaning of very long-term projections. These uncertainties were judged to be such that beyond 104 years projections are not likely to be of the same quality as prior to that timeframe and have to be considered more cautiously.

(iii) Bases for cut-off times

(a) The declining radiological toxicity of the waste

- Cut-off for safety assessment calculations is sometimes argued (at least in part) on the basis of declining radiotoxicity of waste i.e. declining “intrinsic risks” (Nagra, BfS/GRS-B, Enresa, PURAM, SKI/SSI) coupled to increasing difficulty of making quantitative evaluations of consequences (see below).
- Potentially harmful effects of uranium and its daughters (half lives up to billions of years) cannot be eliminated completely by any repository design (SKB/SKI/SSI).
- Nagra points out that radiotoxicity curves “flatten out” after about 106 to 107 years and stay roughly constant up to about 109 years (Figure 5.9), a time that is clearly well beyond any meaningful cut-off time.

(b) The time of occurrence of peak radiological consequences

- Regulations sometimes require calculation at least to the time of “peak consequences” (e.g. STUK, SSI/SKI,).

- If compliance must be shown up to the time of maximum consequences, the period for safety assessment calculations is determined by the effectiveness of the system in delaying releases (e.g. IRSN).
- Even if a "peak consequence" requirement is not part of regulations, the period covered by safety assessment calculations is sometimes justified in part by the fact that transport of the most important radionuclides has already occurred by the time the cut-off is reached (Andra/Enresa, in discussing 106 years "key milestone").

(c) The need for adequate coverage of transient processes and perturbing phenomena

- It is sometimes argued that the cut-off time for safety assessment calculations (or for the compliance period) must be sufficiently long (a), that early transient thermal, hydraulic, mechanical (THM) processes are largely complete (see also (i), above), and (b), that key perturbing phenomena that may occur in the future will have arisen, such that the robustness of the repository with respect to these phenomena is tested.
- For example, the 104 years compliance period in US regulations for Yucca Mountain (now vacated and proposed to require a million-year calculation) was argued in part on the basis that it is sufficiently long that a wide range of conditions will occur that will challenge the multi-barrier system, providing a reasonable evaluation of repository robustness. In addition, the US requirement to address any potentially disturbing phenomena with a probability of occurring greater than 10^{-8} per year intentionally pulls in low probability scenarios to ensure robustness of the system.
- In issuing its generally applicable regulations for land disposal of spent nuclear fuel, high-level waste and transuranic radioactive waste (40 CFR part 191), US EPA stated that 104 years is long enough to distinguish repositories with good isolation capabilities from those with poor ones, but it is short enough that major geological changes are unlikely and repository performance might be reasonably projected. In addition, when this regulation is applied at WIPP, 104 years is a justifiable timeframe since the only scenarios that result in a dose from the WIPP repository are intrusive scenarios that have their greatest consequences early in the repository's history.
- As noted for the Yucca Mountain case above, here also the requirement includes considering potentially disturbing phenomena with a probability of occurring greater than 10^{-8} per year, bringing low probability scenarios into the 104 years calculation.
- In Sweden, regulations state that (among other considerations) the period covered must at least include one glaciation cycle (105 years) to shed light on the strains that this might place on the repository. No consideration is required of the period beyond 106 years.

(d) Concerns of stakeholders

- Nirex (cut off in its generic performance assessment at 106 years) also mentions the concerns and expectations of stakeholders, as well as UK regulatory guidance (above).

(e) Increasing uncertainty at longer times

- Some regulations/guidelines require or recommend safety to be demonstrated only as long as geoscientific prognoses can be made (106 years in German Draft Criteria) – the situation of selecting a site so that the compliance demonstration is less demanding because of a lack of site stability is clearly to be avoided – therefore requirements on site stability may also be an important feature of such regulations. According to the AkEnd recommendations, the basis for regarding geoscientific prognoses over a 106 years time frame as reasonable is that chosen sites can be well characterised and that their evolutionary histories can be traced back and interpreted over geological periods (GRS-K).

- In UK regulations, "no definite cut-off in time is prescribed either for the application of the risk target or the period over which the risk should be assessed. 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. At times longer than those for which the conditions of the engineered and geological barriers can be modelled or reasonably assumed, scoping calculations or qualitative arguments may be used to indicate the continuing level of safety."
- Current understanding of the Finnish regulator is that no rigorous quantitative safety assessment is required for the "farthest future".
- The US NAS recommended that compliance assessment be conducted up to the time of greatest risk at Yucca Mountain, "within the limits imposed by long-term predictability of both the geological environment and the distribution of local and global populations." The US NAS considered that such assessments could be performed up to 106 years, which would constitute the period of geological stability. US EPA standards for Yucca Mountain are required by law to be consistent with recommendations from the US NAS (US EPA).
- Suitable sites can be well characterised and have quiet evolutionary histories that can be traced back and interpreted over "geological periods" (Germany) – in practice, this typically means geo-histories greater than a few million years to allow prognoses for about a million years.
- Some implementers also choose to cut-off safety assessment calculations when such prognoses can no longer be supported – or when scientific knowledge does not support meaningful modelling (ONDRAF/NIRAS).
- Enresa analysed a generic site and concluded that the issue of geosphere stability could not be properly addressed in such a case. Doses were calculated up to 106 years – site-specific assessments might address a different timeframe – although longer-term calculations would be considered in order to ensure no very late-time peak consequences.

Value and definition of time frames (Question 2.3)

- Timeframes set by regulators may reflect judgements regarding uncertainty in the projections that are made – and whether it is justified to compare these projections with quantitative standards (US EPA/US NRC).
- Regulations may set out consecutive series of time frames and cut offs for which the requirements for the assessment decrease in a stepwise manner as the timescale increases (SKI/SSI, STUK, AVN, proposed US EPA standard) – see Box A4.1.

Box A4.1: **Example from Finland of time frames set by regulations**

1. The period extending to several thousand years – the “environmentally predictable future”: exposures to humans are reasonably predictable, albeit there will be environmental changes.
2. The period from about 10 000 years to a few 100 000 years (the “era of extreme climatic changes”: activity of the spent fuel decreases to a level of the uranium ore it was mined from, indicating reduced risk. Uncertainties are large. Very uncertain biosphere scenarios.
3. The “farthest future”: no rigorous quantitative safety assessment will be required beyond the time period starting from about a few 100 000 to a million years in the future. However, qualitative considerations, such as bounding analyses with simplified methods, comparisons with natural analogues or arguments based on the geological history of the site will be required for the safety case.

- Many programmes find that division of time into time frames is valuable as a structuring approach (but for some not a necessity – PURAM) in carrying out safety assessments, evaluating/treating uncertainties and constructing safety cases (e.g. SKB, Nirex, Andra, ONDRAF/NIRAS, Nagra).
- Some responses mention “natural time frames” that emerge in the course of safety analysis, and reflect the evolution of the repository, changing uncertainties and the changing way that the repository provides safety (ONDRAF/NIRAS, ENRESA, Andra, Nagra, Nirex, PURAM, SKB).
- There are nevertheless various ways in which a division into time fames may be made – e.g. time frames dominated by a limited set of processes and coupled processes (Andra, SKB), changes regarding each system component’s role in providing safety (PURAM), FEPs occurring that may affect the safety of the repository (Nirex), lifetime of repository (ONDRAF/NIRAS; PURAM). The choice made may also reflect “national culture”.
- Five time frames are identified in the currently discussed Safety Philosophy by the implementing organisation (BfS/GRS-B) – see Section 5.5.2 of main text for further examples.
- These natural time frames may not have fixed start and end points, due to uncertainties in the rates of processes and the timing of events – timeframes may also overlap (IRSN; Nirex).
- Time frames are generally the responsibility of the implementer to define and justify.
- The initial period (“thermal phase” for spent fuel and high-level waste) can usefully be singled out – complex and uncertain transient effects are counterbalanced in many concepts by complete containment in this period (e.g. responses to Question 9.2).
- Other specific time frames mentioned in regulations are given in responses to Question 2.1. In addition, the responses of implementers include:
  - the (site/host-rock specific) time frame within which significant geological changes are highly unlikely – approximately 10^6 years for Nagra’s Opalinus Clay and Andra's Callovo-Oxfordian clay.

  - the time frame when “waste poses an unusual hazard” (at least in terms of radiological toxicity by ingestion) – 106 years for spent fuel and high-level waste – based on analyses of the decrease in radiotoxicity with time and comparison with the radiotoxicity of the host rock and of ore bodies (see responses to Question 9.1); and
  - the time frame for which results of calculations of quantitative safety indicators are shown – up to 107 years (Nagra) – *vs.* longer time frame for more qualitative arguments – based on both of the above – the period between 106 years and 107 years is considered to be subject to significant uncertainties, and is shown only to indicate the evolution of the shape of the calculated curves.

- PURAM and Nirex mention that different safety indicators can be appropriate in different time frames. This is explicitly laid down in Finnish regulations (STUK) and Swedish (SSI) guidelines.
- Swedish regulations specify that the biosphere needs to be described accurately up to 103 years after closure, based on current conditions and known trends (SKI/SSI).
- AVN mentions that time frames can be useful (among other things) to ensure that the effort spent analysing safety reflects the hazard potential of the waste.

Questionnaire Section 3: Evolving role of the system components

Guidelines, requirements or principles related to stability or durability of system components (Question 3.1)

(i) General remarks about subsystem criteria, etc.

- Flexibility in regulations regarding the multiple components of a repository exists – a reduced component performance is compensated by enhancing the performance of others (e.g. ONDRAF/NIRAS).
- Sub-system criteria could undermine the responsibility of the implementer to take full responsibility for the safety case (SKI/SSI).
- In general, it is the performance of the system as a whole that is ultimately important, and not the performance of individual components (ONDRAF/NIRAS, US NRC and others) – regulations mostly concern whole-system performance.
- Generic regulations in the US (10 CFR Part 60, which is not applicable to Yucca Mountain) specify e.g. minimum lifetime range for the engineered system, minimum groundwater travel time (when the Part 60 subsystem criteria were selected in the 1980s, they were intended to be separate, “independent”, easily determined measures of subsystem performance, determination of which would require only application of technology that was readily available – since that time, extensive experience with site-specific performance assessment has shown them to be none of these).
- Thus, the US regulations for Yucca Mountain (10 CFR Part 63) chose not to specify quantitative subsystem requirements and adopted a different approach for understanding the capabilities of the repository’s barriers within the context of the overall performance assessment.
- Often, there are general requirements on host rock characterisation and geosphere/engineered barrier characteristics, not specifically related to timescales (e.g. German Draft Criteria, French safety rule).

- In Germany a requirement for no “exceptional developments” of the repository system that could result in releases to the biosphere within 104 years is under consideration – i.e. the time frame during which the barrier system is subject to only minor changes (BfS/GRS-B, currently discussed Safety Philosophy by the implementing organisation).
- Some regulations contain elements that indirectly relate to the stability or durability of some system components – e.g. monitoring of system evolution for unexpected change during a prolonged surveillance period after waste emplacement (e.g. US EPA regulation and Swiss legal requirement); avoidance of sites where exploration for resources has or could be expected to take place (several national regulations); minimum time when retrievability must remain an option (US NRC/US DOE).
- The implementer generally derives performance requirements/targets on each barrier iteratively in the course of concept development and safety assessment (e.g. STUK) – examples include requirements on canister wall thickness, canister strength, peak canister/buffer temperature, and respect distances to faults (e.g. SKB).

(ii) Stability and repository depth/layout

- Requirements on repository depth include, for example, in Finland, a requirement for “sufficient depth in order to mitigate the impacts of above-ground events, actions and environmental changes on the long-term safety and to render inadvertent human intrusion to the repository very difficult” (STUK).
- There can be requirements on layout in relation to large fracture zones designed to avoid risk to canister integrity from large post-glacial earthquakes (SKB).

(iii) Geosphere stability

- The French safety rule states that geosphere stability is to be demonstrated for at least 104 years – see also 4.1.
- In Swiss regulations, no time frame for geosphere stability is specified.
- In German Draft Criteria, predictability for at least 106 years is recommended (GRS-K).
- In Finnish regulations – stability up to at least several thousands of years is required
- SKI/SSI note that some degree of geosphere “instability” may be compensated for in engineered barrier design.
- In Japan, general requirements for a repository site are set down in law; siting factors for selection of preliminary investigation areas have been defined by NUMO.
- OPG mentions that a precise statement of “durability” of the geosphere is probably not required due to the age of rock and groundwater.

(iv) Engineered barrier components

- Mostly, the durability of system components is studied and assessed, but not laid down as “requirements”.
- The KBS-3 copper canister with cast iron insert is designed to provide isolation for the 106 years assessment period in Sweden – criteria on the host rock are defined to ensure canister maintains its integrity if these criteria are met (SKB).
- The KBS-3 buffer is selected with regard to its chemical stability in the expected environment (SKB).
- Quality assurance for the fabrication/emplacement of the engineered barrier system is required in order to ensure that the expected function is realised in practice (NUMO/JNC).
- OPG mentions durability requirements or goals for containers are to be set by the desired period of easy retrieval, but this period has not yet been defined in Canada.
- In Germany, there should be a high probability that high-level waste packages are still in a state in which they can be handled safely during the 500-years time frame of passive institutional control (currently discussed in the Safety Philosophy by the implementing organisation, BfS/GRS-B).
- Some national agencies refer to a complete containment period for high-level waste and spent fuel during the period of high heat output, radiotoxicity or α/ß radiation fields (e.g. Andra, ONDRAF/NIRAS – from a few hundred years (vitrified wastes) to several thousand (spent fuel); Nagra – at least 103 years).
- In some countries, the implementer has established a requirement for a period of complete containment by canisters (e.g. at least 103 years – Enresa, NUMO/JNC).

The evolving mechanisms by which a disposal system provides safety (Question 3.2)

- Various components of the repository/safety functions are expected to provide greater or lesser contributions to performance over time (US NRC, ONDRAF/NIRAS, Andra) – i.e. barrier emphasis changes over time (US DOE).
- Some organisations utilise the concept of “latent functions” that would operate earlier if another part of the system ceased to operate earlier than expected, or provided poorer than expected performance (Nagra, ONDRAF/NIRAS, SKB). For instance, containment for 106 years assessment period is expected in KBS-3 concept; latent functions may come into play if canister failure does occur – see also Figures. 3.1 to 3.3 in main text.
- Emphasis in some cases tends to shift from engineered barriers to geosphere over time (e.g. NUMO/JNC, ONDRAF/NIRAS, Andra, Nagra).
- The geosphere often provides the most important/most reliable barrier in the very long term –and is required to do so in the French safety rule.
- In Sweden, the engineered barriers play a critical role over the entire period for which geological stability can be assured.
- A key transition in most spent fuel/high-level waste systems is between the period of complete containment by canisters/overpacks and the period thereafter – sometimes corresponding approximately to the “thermal phase” – about 103 years – but may be significantly longer (e.g. in the Swedish/Finnish concepts).

- This transition may be assumed instantaneous, or may be modelled as being the result of gradual changes in operative processes.
- For a repository in rock salt, closure of the vaults by (temperature dependent) salt creep affects when the host rock reaches its "target state" – after several hundred years for spent fuel/high-level waste; after several thousands of years for less heat-producing wastes (GRS-K) – there is a corresponding transition from emphasis on properties of engineered barriers (seals/backfill) to emphasis on the geosphere in providing safety.

Questionnaire Section 4: Geosphere stability

Events and processes that could affect how the safety role of the geosphere changes over time (Question 4.1)

- In Germany, the "isolating rock zone" (which is defined as part of the geological barrier which at normal development of the repository and together with the technical and geotechnical barriers has to ensure the confinement of the waste for the isolation period) should serve as a migration barrier over 106 years, while other parts of the geosphere provide a protective environment for the isolating rock zone (AkEnd recommendations).
- In the case of Yucca Mountain, the geosphere also has an important early role in limiting the amount of water infiltrating into the emplacement drifts – part of providing a favourable environment around the waste containers (US DOE).
- The barrier role of the geosphere in particular especially emphasised e.g. in Germany (historically focused on disposal in salt e.g. AkEnd recommendations) and in Swiss/French/Belgian studies of disposal in plastic sediments.
- The French safety rule states that in the long-term (after substantial decay has taken place, but no time frame specified) the geological barrier (together with access tunnel seals) must alone provide adequate containment capacity – although a high performance engineered barrier system is not ruled out.
- Repository-induced changes and natural changes can be distinguished – the latter generally become significant only in the long-term (sites chosen for stability) – e.g. sites generally selected such that e.g. uplift/erosion do not affect safety roles for a prolonged period (at least a million years – Germany/Nagra – although glacial rebound may remain important in Finnish/Scandinavian cases).

(i) Repository-induced changes

- Potentially important repository-induced changes have to be considered (examples from ONDRAF/NIRAS):
  - irreversible thermally induced chemical/mineralogical/hydrogeological changes;
  - disturbances caused by creation of gas pathways (thought to be reversible in plastic clay);
  - repository-induced chemical disturbances.

These issues are being studied, but are not believed to be problematic – and could probably be engineered around to some extent.

(ii) Natural changes (general)

- In general, within the period of geological stability (106 years, say – see 3.2), there are no natural events and processes with a significant probability of occurrence that affect the isolation/barrier roles of the geosphere at the sites under consideration, although the barrier performance may change over time, and events and processes are identified that could significantly perturb the engineered barriers.
- Prognoses regarding natural changes are generally based on understanding of site history – e.g. diagenesis has been slow in Boom Clay for the past 30 million years (ONDRAF/NIRAS); Yucca Mountain has remained essentially unchanged for several million years (US DOE).
- Safety roles of the geosphere are potentially detrimentally affected by:
  - seal failure (Enresa);
  - human intrusion (boreholes) (IRSN, BfS/GRS, PURAM, STUK, NUMO/JNC);
  - subsidence/uplift/subrosion/erosion (Andra/IRSN, BfS/GRS, PURAM, STUK, NUMO/JNC);
  - development of fracture coatings (IRSN);
  - fracture creation/opening/change of transmissivity (Nirex, Enresa, IRSN, PURAM, BfS/GRS – less important for plastic clays and for a repository in salt);
  - the possibility of repository-induced stresses leading to brine inflow (GRS-K);
  - seismic activity occurring in the long term (French safety rule).

(iii) Geological events and processes

- Changes associated with large-scale tectonic activity are generally relevant only at very long timescales (e.g. > 106 years, Nirex) for a well-chosen site.
- No significant detrimental effects are expected in the first 106 years for Swiss Opalinus Clay.
- Up to 10 000 years, it is expected that the stability of the host formation should be demonstrated (French safety rule). During this period of time, no event or process is expected to affect the safety role of the geosphere.
- Some transient effects may occur that do not affect the main safety roles of the host rock – dissipation of overpressures (clay host rock) and uplift, subrosion/erosion, glaciation, tectonic movements (salt host rocks, Germany).
- Positive effects that include salt creep (Germany) and the self-sealing capacity of plastic clays may determine the timescale for closing of underground openings/EDZ fractures, etc.
- Igneous activity is important for some programmes, depending on geological context (Japan, US/Yucca Mountain).
- In the case of Yucca Mountain, seismic and/or igneous events that could affect geosphere performance could not be "screened out"[2] in the FEP selection process based solely on low probability – the most important consequences of such events are to engineered barriers (US DOE).

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[2] US-EPA has established a "reasonable expectation" standard and designated a screening probability for very unlikely events – intended to avoid overly speculative scenarios.

- Sometimes it is possible to deal with potential reactivation of faults/fissures by siting the repository away from existing fault zones (ONDRAF/NIRAS).
- For ERAM, Germany, the properties of the caprock may change due to changes in the natural stress field, resulting in an alternative scenario involving water in- and outflow via the caprock (BfS/GRS-B).

(iv) Climate change

- Climate change has minor effects at repository depth for many concepts, and does not affect engineered barriers or the safety role of host rock (e.g. US DOE/WIPP).
- The severity of the impact of future glaciations is host-rock specific (and is judged to be minor for some sites, e.g. in the Nagra case). For ERAM, due to uncertain knowledge of the impact of a glaciation, the hydrogeological model was not regarded as reliable after 150 000 years (BfS/GRS-B).
- Erosion and sedimentation (geomorphological evolution) as a result of climate change/ glaciation and subsidence/uplift may affect mostly overlying formations (at least up to 106 years, say, for a well-chosen site) – often no safety role is assigned to these formations – but some potential impact on hydrogeological circulation and dilution are assessed (Andra, Nirex).
- Climate change could conceivably affect deep groundwater chemistry (precipitation and dissolution) (Nirex) – in the case of Yucca Mountain, it affects infiltration into the repository layer (US EPA).
- Permafrost and glacial episodes are specifically mentioned by SKB/SKI/SI as implying additional chemical and mechanical loads on the engineered barriers – e.g. increased hydrostatic pressure, higher probability of earthquakes, and penetration of oxidising melt water.
- Climate-related changes affecting geosphere transport barriers is less important in KBS-3 than in some other concepts, although transient effects during periods of relatively rapid (climate) change may be important (SKI/SSI).

Limits to how long the geosphere can be relied upon to play a role in a safety case (Question 4.2)

- In the US programme, "stability" is defined in terms of the time during which the variability of geological characteristics and their future behaviour can be bounded, or projected within a reasonable range of possibilities (US EPA response to Question 3.1) – does not imply a "static" system.
- No a priori limit to how long the geosphere can be relied upon to play a role in a safety case set by regulation (IRSN, Andra, ONDRAF/NIRAS, US NRC). Furthermore, the French safety rule recommends that the geological barrier should play a major role in long-term safety.
- In Canada, limit would be geological changes as a result of continental drift and interaction between continental plates – 50-1 000 million year time scale (OPG).
- Stability can be argued for 106 years for Yucca Mountain, following the US NAS 1995 recommendation. This in turn defines how long assessments can reasonably be conducted, although some continuing barrier to releases is expected over periods well beyond a million years (US EPA).

- The period over which reliable geoscientific prognoses can be made is given in German Draft Criteria as 106 years.
- The barrier role of the geosphere may be perturbed over a shorter time frame, e.g. by fracturing, glaciation (BfS/GRS-B), but the geosphere is expected to continue to provide isolation and a protective environment.
- The ultimate limit may stretch into timeframes where major geological upheavals are expected to occur – approx 107 years (SKI/SSI) – 106 years for a generic (well chosen) site (Enresa, Nirex).
- In Sweden, it is expected that the key roles of the geosphere of isolation and protection of the engineered barriers will be maintained throughout the 106 year assessment period – transient recurring phenomena like post-glacial faulting and alterations to groundwater chemistry during glacial conditions require careful evaluation (SKB).
- Stability of the geological environment over 105 years provides a basis for the safety assessment time frame – but needs to be determined on a site-specific basis (NUMO/JNC).
- For Opalinus Clay, key roles of the geosphere have been shown to be maintained for several million years, although predictions are increasingly qualitative in nature beyond about a million years. On the other hand, the toxicity of waste is substantially reduced after a few million years (Nagra).

Questionnaire Section 5: The influence of the pre-closure phase and period of institutional control on long-term safety and its assessment

Processes initiated prior to repository closure influence time frames in the post-closure period (Question 5.1a)

- Aerobic conditions in the pre-closure phase, and management of groundwater inflow to keep the facility "dry", affect chemical and hydrogeological conditions, which will take time to re-equilibrate (Nirex, NUMO/JNC, Andra).
- Relevant processes include cooling and aging of the waste prior to closure, as well as transient thermal, hydraulic, mechanical, chemical and biological processes (including oxidation, desaturation – in the case of saturated host rocks, formation of an excavation disturbed zone – EDZ, and heat-induced physical and chemical changes in the host rock).
- In the case of Yucca Mountain, pre-closure impacts for a repository in unsaturated rock include the thermal regime at closure, which affects corrosion of waste packages and the amount and composition of water entering the repository. The US DOE has considered impacts of higher – and lower-temperature operating modes. Results suggest minor differences in effects on long-term safety.
- Additional potential impacts from the pre-closure phase on the post-closure system's performance, specific to the Yucca Mountain repository, may include manageable processes such as oxidation of spent fuel from exposure to air during storage and handling, and processes not under US DOE control such as the degree of spent fuel burn up, which may affect the microcrystalline structure of the spent fuel and lead to smaller particle sizes being available for some pre-closure accident scenarios and for one highly unlikely post-closure disruptive event involving spent fuel entrainment in magma (US DOE).

- In Canada, an engineering decision to retain or vent gases produced prior to closure in a low-and intermediate- level waste repository affects timescale for gas build up during the post-closure phase (OPG).
- There is general consensus that the long-term safety impact of disturbances caused by pre-closure activities must be assessed – e.g. the impact of ventilation, oxidation, de-saturation processes on canister/package longevity, gas effects and radionuclide mobility.
- Some organisations have started to evaluate these effects (e.g. SKB, Andra, OPG); in some cases little impact is expected (Enresa, Andra).
- Ensuring minimal adverse post-closure impact is an objective in planning the operational phase (Enresa, ONDRAF/NIRAS, STUK, PURAM, RAWRA).
- For example, methods of construction/operation/closure should be selected to preserve the natural characteristics of the rock as far as possible (avoiding or limiting irreversible changes). From the point of view of safety, a prudent approach is not to keep the system open for any longer than necessary (e.g. ONDRAF/NIRAS, STUK).
- The Yucca Mountain programme has guidelines in place to minimise use of pre-closure construction materials that could have significant effects on post-closure environmental conditions (e.g. concrete – US DOE).
- The design lifetime of spent fuel and high-level waste canisters is, in some cases, determined in part by a wish to avoid the need for detailed modelling of transient processes which may not fully be understood at a given stage in a programme (Andra, ONDRAF/NIRAS, Nagra).
- In the case of a repository in rock salt, convergence by salt creep (which determines a key time frame in repository evolution – see 3.2) is dependent on the developing temperature and stress/strain field, which is in turn dependent on excavation and waste emplacement activities (Germany).
- In case of a rather dry formation like rock salt, water brought to the mine during the operational phase with air, backfill and waste causes early corrosion and gas production even without an external water intrusion, and can therefore influence the temporal development of the sealed disposal areas of the repository during the first several thousands of years (BfS/GRS-B)
- In some cases the start of release of radionuclides from repositories for intermediate-level waste is affected by the saturation time of the repository (where little or no credit can be taken for complete containment by waste packages) (Nagra).
- Scenarios involving “mistakes” in the operational phase are not generally mentioned in responses – except for Nagra's abandoned repository case.

Dependency of these time frames on the duration of the pre-closure phase and treatment in safety assessment (Question 5.1b)

- The pre-closure open phase in some cases could last for as much as several centuries, depending on the demands of society for assuring the ability to retrieve – hence the repository design may have to allow for this, potentially resulting in prolonged exposure of canisters to oxidising conditions (Andra/US DOE).
- A longer pre-closure phase could increase the impact and duration of some transient processes and increase the probability of deposition of extraneous materials in repository areas (SKI/SSI).

- For example, the duration of excavation and waste emplacement activities, and the amount and nature of backfill material utilised, affects the time taken for salt creep to return a salt host rock to its "target state" (Germany).
- Some information from the operation of URLs can be relevant to developing understanding of the impact of the pre-closure phase (SKI/SSI).
- For spent fuel and high-level waste disposal, transient processes initiated in the pre-closure phase may be argued to have ceased by the time of canister breaching – but any irreversible or slowly reversible effects on the final properties of the barriers need to be assessed (e.g. Nagra).
- In many cases, disturbances have not as yet been assessed in detail – in some cases it is argued that effects are likely to be small because of the short duration of the period that emplacement tunnels are planned to be open (Nagra). In other cases, conservative assumptions are made or probability density functions are used to take account of some of the potential variations of properties with time (Nirex).

Duration of post-closure institutional control (Question 5.2a)

- Post closure institutional control is foreseen as a possibility, and may be a regulatory/legal requirement – it is not generally motivated by long-term safety concerns, but rather for security/nuclear safeguards (SKI/SSI; IRSN) and for public acceptability.
- In some countries, there is a period of monitoring required by law, although the duration may not be specified (Switzerland, Hungary).
- Various types of institutional control are considered – active and/or passive measures submitted to control authorities (e.g. AVN); monitoring and surface surveillance (NUMO/JNC).
- Active institutional controls should be used for as long as possible – monitoring using non-intrusive techniques "until there are no significant concerns to be addressed by further monitoring" (e.g. US EPA/WIPP) – but no credit for active institutional control can be taken beyond 100 years in the US.
- Some studies are being carried out to consider what types of monitoring might be used (e.g. Nirex).
- Passive post-closure institutional control may take the form of documentation and multiple record retention systems (e.g. in Japan, the law requires the government to keep records of the repository "permanently") – repository location, inventory and design (Germany, Hungary, SKI/SSI) – land-use control/entry in land use registry – (STUK), construction of markers/monuments and archives (US NRC, US EPA).
- Planning of post-closure institutional control is at an early stage of development in many programmes.
- The duration of active controls is not fixed yet – will probably be a decision of future generations (ONDRAF/NIRAS, OPG).
- 50 years is under discussion for active controls after closure in Germany in the context of the Safety Philosophy by the implementing organisation; 50 years minimum fixed by legislation in Hungary; 100 years foreseen in Czech Republic, but could be shorter.

- In the US, no specific time frame is stated regulations for passive post-closure controls (US NRC, US EPA).
- AVN considers low confidence in upholding (passive) institutional control over more than several centuries after closure.
- Period of passive institutional control foreseen as approximately 500 years (French safety rules) or under discussion (Germany, Spain, Belgium).
- A 500-year period is supported by feedback of real experiences of maintaining memory and records (e.g. "permanent paper" – Andra).
- Period of institutional control can be considered as part of the defence in depth approach (Andra, ONDRAF/NIRAS). The 500 years period suggested by the French safety rule is partly supported by feedback of real experiences of maintaining memory and records (e.g. "permanent paper" – Andra).
- Mining activities have been recorded in Germany since the Middle Ages and these records are still being used today.

Influence of post-closure institutional control on long-term safety and its assessment (Question 5.2b)

- Safety should not be reliant on any period of post-closure control and monitoring, and should not be adversely affected by it – although a period of control may be considered or be required by law – e.g. in the interests of preserving evidence and for quality assurance purposes (Germany, SKI/SSI and others).
- Surveillance measures or measures to facilitate retrieval should not compromise passive safety (US, Switzerland, Swedish regulatory requirement). If undertaken; they may be used to confirm certain aspects or assumptions of a safety assessment. In the case of spent fuel and high-level waste, such measures, if taken, must be analysed and reported (SKI/SSI).
- PURAM mentions that, in principle, a period of institutional control allows time for the investigations of new technologies for waste treatment and may contribute to acceptability.
- Safety assessments in some cases assume that a period of post-closure institutional control (plus historical memory, designation of site by "permanent" markers – Enresa) eliminates some human intrusion scenarios while the controls are in place (Belgium, Canada, Germany, Spain, France, Switzerland, United Kingdom, and United States).
- In the case of the US WIPP repository, assessments may not assume presence of active institutional controls beyond 100 years after closure – though they may remain in place for much longer times (US EPA/WIPP).
- Otherwise, because the period over which controls can/will be maintained is highly uncertain, no credit is taken for institutional controls in safety assessments. For instance, UK regulations state that it is not acceptable to base a safety case on maintaining control of a site for more than, at most, a few hundred years.
- Monitoring – e.g. of gas levels – could allow corrective actions to be taken should problems be detected – but such measures are not part of any safety case (Nirex, US NRC/US EPA).
- Period of 500 years ensures that transient (THM) phase will be complete or nearly so by the time human intrusion needs to be considered – simplifies modelling of consequences of intrusion (Enresa).

Questionnaire Section 6: FEPs and scenarios

Characteristic timescales of key processes defining the expected evolution and performance of systems (Question 6.1a)

- Characteristic timescales are subject to uncertainty and may be waste-stream and radionuclide dependent – e.g. some radionuclides are much more strongly retained than others (Nirex).
- Many processes occur over broad time frames – e.g. release from waste form, thermal evolution and repository resaturation.
- Some examples of characteristic timescales for internal processes are given in Table A4.2.
- In the case of external processes, significant (natural) climate change is expected to occur after thousands of years for the first major alteration, then cycles of tens of thousands of years up to 105 years (Sweden, Finland).
- In the Swiss case (Opalinus Clay), uplift and erosion potentially leading to significant loss of overburden is expected to require in the order of several millions of years or more (Nagra).

Table A4.2: **Examples of key processes and characteristic timescales (see Appendix 3 for repository concepts on which responses are based)**

Process	Characteristic timescales
General (processes not host-rock specific - although timescales may be)	
Temperature perturbations as a result of heat generation by spent fuel and high-level waste	A few hundred to a few thousand years (Nagra)
	A few thousand years for vitrified high-level waste, 10^4 years for spent fuel (Andra)
	10^4 years, but peak temperature reached after 7 years for clay and 24 years for granite (Enresa)
	Several centuries to several thousand years (AVN)
	Peak at 10 years in the engineered barrier system and at 10-100 years in the host rock (ONDRAF/NIRAS)
	Tens to hundreds of years (SKB)
	Boiling of water in rock ceases before 2 000 years, temperature effects unimportant by 10^4 years (US DOE)
Corrosion of waste packages; breaching of spent fuel/high-level waste canisters	See Table 3.1, main text.
Preferential leaching of a fraction of the spent fuel inventory originally located in the gap between fuel pellets and cladding and at grain boundaries	A few days (gap) to years (grain boundaries) following canister breaching (Nagra)

Dissolution of vitrified high-level waste	10^5 to 10^6 years (Nagra)
	Several thousands of years (ONDRAF/NIRAS)
Dissolution of the spent fuel matrix	Millions of years or more (Nagra, Enresa – although treated more pessimistically in Nagra safety assessment)
	Hundreds of thousands of years ONDRAF/NIRAS)
	Hundreds of years for oxidation in an unsaturated environment (US DOE)
Oxidation of vitrified high-level waste/spent fuel in an unsaturated environment	A few thousand years for vitrified high-level waste; a few hundreds of years for spent fuel (US DOE)
Radionuclide transport through the rock	In the order of hundreds of thousands of years for non-sorbing species, and longer for sorbing species (Nagra)
	In the order of 10^4 years for non-sorbing radionuclides (ONDRAF/NIRAS)
	10^6 years by diffusion (OPG)
Radioactive decay	Wide range of timescales, but can be as long as a few billion years
Repositories in saturated host rocks	
Resaturation of the repository near field (generally rather uncertain timescale – often assumed instantaneous in safety assessment)	In the order of a few hundred years (Nagra)
	A hundred to a few thousand years for swelling clay seals (Andra)
	20 years for both clay and granite host rocks (Enresa)
	A few tens of years to thousands of years (ONDRAF)
	1-50 years (PURAM)
	Tens to hundreds of years (SKB)
Transient oxidising conditions in the repository near field	A few decades (ONDRAF/NIRAS)
	102-104 years (PURAM)
	About 103 years (OPG)
Gas build-up	About 102 years (OPG)
Repositories in clay	
Mechanical evolution of the repository (e.g. tunnel convergence for a repository in clay)	105 years (Andra)
Resealing of EDZ fractures in clay	A few months to years (ONDRAF/NIRAS).
Chemical evolution	Chemical processes can continue after one million years (Andra)

Repositories in salt formations (general – based on ERAM repository – BfS/GRS-B)	
Brine displacement due to gas formation	About 102 years
Degradation of repository seals followed by flooding of disposal areas	About 104 years
Convergence-driven outflow from flooded areas (for altered evolution scenarios)	106 years or more
Repositories in salt formations (heat-producing waste – GRS-K)	
Tensions in a rock salt host rock caused by heat producing waste	102 years
Uplift (reversible) of the host rock caused by heat producing waste	In the order of 103 years
Closure of the vaults by salt creep	After several 102 years for spent fuel and high-level waste; after several 103 years for less heat-producing wastes

Link between these timescales and the division of the post-closure period into time frames (Question 6.1b)

- There can be "natural time frames" – see Question 2.3 – their use and definition is generally a matter for the implementer to determine, propose and defend, based on site/concept-specific scientific understanding of a system and its evolution.
- In the case of the 104 years timeframe in US regulations applicable to the WIPP repository, there is no formal link between this and process timescales – although thermally driven transient processes have their greatest effect in this period (US DOE).

Uncertainties or perturbing phenomena that can lead to alternative scenarios or deviations from the expected path of evolution (Question 6.2a)

(i) General observations

- An exhaustive and structured analysis of uncertainties, perturbing phenomena and alternative scenarios is generally a regulatory requirement, but the identification and treatment of specific uncertainties and perturbing phenomena are generally matters for the implementer.
- Early time changes tend to relate to repository-induced processes – e.g. thermally driven changes in the case of Yucca Mountain.
- Some regulations specify that alternative models that are consistent with available data should be considered in assessments (e.g. US NRC).
- Regulators sometimes specify some phenomena that should (as a minimum) be considered in assessments – examples of phenomena all or some of which are specified in the French safety rule and in Finnish and US regulations as necessary to consider are:
  - Major climate change (either natural or anthropogenic).
  - Exceptional vertical movements.
  - Long-term seismic activity.
  - Release of radionuclides affected by human actions.

  - The presence of a “dysfunctional barrier” (e.g. canister failure during THMC transients).
- Some phenomena require further technical evaluation before appropriate handling in scenario selection can be determined (e.g. SKB).

(ii) Climate change

- Most programmes consider that climate effects may begin to become prominent in a time frame beginning a few tens of thousands of years in the future.
- In Swedish regulations, perturbations associated with climate change are not to be regarded as deviations from expected evolution, but are to be included in it – at least one full glacial cycle should be analysed (105 years) (SKI/SSI).
- On the other hand, French Safety Rules indicate that major climate change and other exceptional natural events are to be regarded as “perturbing phenomena” as long as they occur after 105 years, and need not be viewed as part of the expected evolution.

(iii) Geological change

- Regarding geological changes, the US implementer has produced two (low probability) scenario classes for Yucca Mountain to be included in the compliance assessment – the igneous (volcanic eruption and igneous intrusion) and seismic scenario classes (US DOE).

(iv) Human intrusion

- The (stylised) characteristics of perturbations due to inadvertent human intrusion to be considered in assessments are set by regulations in the United States (US NRC, US EPA) – elsewhere, this is a matter for the implementer.
- Additionally, at WIPP, the probability of human intrusion is based on historical records of drilling and mining at the site (1 in 100 in each century over the 104 years compliance period) (US EPA).

(v) Other examples of potentially perturbing phenomena and uncertainties

- Mechanical and chemical disturbances or interactions between system components, the rates and extent of which are often uncertain (IRSN).
- Deficiencies in or failure of seals (Enresa, IRSN, ONDRAF/NIRAS).
- Gas build up and release of radionuclides as volatile species along gas pathways (IRSN, Nagra, ONDRAF/NIRAS).
- Criticality (Nirex, US DOE).
- Defects in fabrication, construction and installation of the engineered barriers (incomplete overpack sealing, poor backfilling of tunnels, defects in plugs) (NUMO/JNC).
- Fault activation (ONDRAF/NIRAS, PURAM).
- Undetected heterogeneities in the host (clay) formation (French safety rule).
- Hydraulic properties of major water-conducting features in hard rocks (Enresa).
- “Isolation failure scenarios” – i.e. very low probability but potentially high consequence events and their consequences, including magma intrusion into the repository, intersection of

the repository by a new fault (US DOE), repository exposure at the surface following uplift/erosion (NUMO/JNC).

- For a repository in rock salt, the possibility of undiscovered brine pockets, which, when coupled to the possibility of irreversible or slowly reversible repository-induced stresses, leads to the possibility of brine inflow to the repository (GRS-K).

Types of deviation from the expected path of evolution that may arise over time and their relevance in different time frames (Question 6.2b)

- Many deviations can be excluded over a certain time frame, but can occur at essentially any time thereafter – e.g. human intrusion (6.2c, below). There are also "isolation failure scenarios" which could occur, in principle, at any time after the period in which geosphere stability can be assured (NUMO/JNC).
- Some perturbing phenomena can occur continuously but at a very slow rate (e.g. NUMO/JNC uplift/erosion) and only become potentially significant in the very distant future, their exact significance depending e.g. on the degree of radioactive decay of the waste and the extent to which it has dispersed when the repository becomes exposed at the surface.
- Some have a low and temporally constant probability of occurring – e.g. annual probabilities for igneous and seismic events at Yucca Mountain – but (radiological though not necessarily non-radiological) consequences are generally time-dependent because of radioactive decay (US DOE).
- For some organisations, major climate change scenarios (glaciation/permafrost) are not expected earlier than about 104 years in the future (significance of the event depending on the national context and in particular on the location of the potential repository).
- Sometimes, timing strongly affects consequences – gas generation before canister breaching has limited effects, but can provide a medium for transport after breaching (ONDRAF/NIRAS).
- Timing is often uncertain due to incomplete system understanding and variability – e.g. in the case of the release of radionuclides as volatile species, timescales are determined by the rate of gas generation, the physics of pathway formation and the timescale of complete containment by canisters, all of which are subject to uncertainty (BfS/GRS-B and others).
- In some cases, it is conservative to assume that deviations occur immediately and last for all time (Enresa).
- In France, human influence on climate is taken into account via a scenario in which the next glaciation is delayed, based on specific evaluation performed in the context of the BIOCLIM project (Andra).

The period over which the possibility of human intrusion must be considered (Question 6.2c)

- The occurrence of human intrusion is always speculative (SKI/SSI, OPG) and appears after a fixed period (see discussion of institutional control period, Chapter 4).
- At Yucca Mountain, human intrusion is considered unlikely, but there is no basis for specifying probability (unlike WIPP, where intrusion is the most important scenario, and probability can be based on rate of past drilling in the area). The stylised calculation to be performed is specified by regulation (US NRC, US EPA); US DOE must determine the earliest time that the intrusion specified in the standard could occur (see below).

- There is generally, no "cut-off" time specified or assumed for the possibility of human intrusion (except where a cut-off time is set for the assessment as a whole, or for the compliance period) – the possibility of inadvertent intrusion exists at all times after (active) institutional control has stopped, and becomes more likely with time, although the probability is low while site markers, archived records, or "folk memory" remain (Nirex).
- The possibility of human intrusion (e.g. in the form of boreholes intercepting or perturbing a repository) must be considered at any time after the passive institutional control period – i.e. when records of the repository may have been lost – with a time-independent probability (Canada, Switzerland, Spain, Germany, France, Hungary, Czech republic, Japan).
- Geophysical anomalies caused by the repository could conceivably attract inadvertent intrusion (Nirex).
- Human and societal habits/technologies become unpredictable over a timescale that is much shorter than those considered in assessments. In assessing the likelihood and consequences of human intrusion, stylised human intrusion scenarios are often based on present-day habits and technologies (e.g. GRS-K, Nirex, US EPA) – only transient conditions within the repository system are considered, not within society.
- In calculating the consequences of human intrusion, the intrusion event is sometimes assumed to occur immediately following the lapse of institutional controls – this is considered conservative due to the decline of the radioactivity of the waste with time (ONDRAF/NIRAS, Enresa, GRS-K).
- In addition, for some systems (ERAM), intrusion at later times (> 20 000 years) may be omitted from assessment cases because degradation of seals, for example, is such that preferential transport pathways already exist that by-pass the undisturbed geosphere and the creation/abandonment of an exploratory borehole would not result is a significantly less favourable situation (BfS/GRS-B).
- Specific case of direct penetration of a metal spent fuel/high-level waste canister (using present-day technology) may require weakening of the canister by corrosion before a driller would be unaware that penetration has occurred, and if so can be excluded for a longer period (ONDRAF/NIRAS, Nagra, US EPA).
- The effects of future climate in assessing risks from human intrusion are not taken into account as yet (Nirex).

QUESTIONNAIRE SECTION 7: Modelling approaches

Application of modelling approaches when analysing system performance in different time frames (Question 7.1)

- The selection of modelling approaches is a matter for the implementer in most programmes.
- Detailed modelling (e.g. THMC modelling of engineered barrier evolution) is probably more justifiable (and relevant) at early times, with increased use of simpler approaches/bounding calculations for speculative scenarios at later times (SKI/SSI).
- Modelling approaches are generally tailored to the characteristics and evolution of the system under consideration (Andra).
- Rather than discrete changes in approach from one time frame to the next, there is a general shift towards greater simplification/conservatism/stylisation as time increases (PURAM).

- In the US, the application of FEP screening arguments is based primarily on an assessment of their probability within the initial 104 years of the compliance period and their potential consequences – the continuing validity of these arguments is to be assumed thereafter (US DOE)
- US DOE uses a fully probabilistic approach even at long time frames (> 104 years), even though US EPA regulations (now vacated and remanded to US EPA for revision – see Appendix 3) imply that another approach (e.g. limited deterministic calculations) could also be legitimate at these times (US DOE).
- SKB carries out detailed hydrological modelling for the current interglacial period, and adopts a more stylised/simplified approach thereafter, due to increasing uncertainties and also model limitations.
- Models should represent relevant features and processes in each time frame in an appropriate degree of detail (e.g. near field heterogeneity may only be relevant at early times – Nirex). Some "process models" may only be applicable in specific time frames (see, however, 7.3).
- Andra mentions different model bases for processes that can be directly observed as compared with slow processes that can only be indirectly inferred, such as from field observations and analogues (this has "validation" implications as well).
- Different modelling approaches may be required to analyse different scenarios (e.g. ONDRAF/NIRAS), and some scenarios may relate to specific time frames (e.g. the time frame after the occurrence of a human intrusion event).
- A simplified approach is used for the subrosion scenario for high-level waste repository in rock salt. This is justified due to the long period of time before the scenario becomes significant – radionuclide release starts later than 1 million years, hence the detailed information about the geometry of the mine at the present time is questionable (BfS/GRS-B).
- "Static" stylised representations of the biosphere may be used, to "decouple" uncertainties in barrier system evolution from uncertainties in biosphere evolution (Andra, ONDRAF/NIRAS).
- Where alternative safety indicators are used, different modelling approaches for at least some aspects of the system may be required. This may impose less stringent requirements on model/database validation for parts of the system, which is generally an important reason for adopting these alternative indicators (see also 9.1a).
- According to Finnish regulations, no biosphere modelling is required after several thousand years.
- Arguments based on decreased radiotoxicity of the waste may be employed at later times, when the basic model assumption of geosphere stability can no longer be assured and is not required as part of the argument (Nagra) – see however, limitations of arguments based on radiotoxicity (Section 5.4 of main text).

Stringency of regulatory requirements on the justification of model assumptions in different time frames (Question 7.2)

- There is no specific regulatory guidance on the degree to which models/databases need to be "validated" in different time frames – although discussions are still underway in Germany, Canada and the Czech Republic.

- However, a lower confidence in the assumptions underlying models is the basis of the US EPA argument for proposing a different dose limit requirement for the period up to 104 years as compared with the period after 104 years.
- For the very long-term, it must be recognised that detailed modelling of all possible processes is neither possible nor required (e.g. comments of PURAM for times beyond 104 years).
- The degree of justification required for specific assumptions can depend on the impact of these assumptions on the calculated levels of safety or on the safety case – i.e. may be determined *a posteriori* (IRSN, AVN, SKI/SSI). In Japan, NSC suggests assessments should focus on the time period when they are more reliable – e.g. the first few thousand years after disposal.
- Regulations sometimes recognise that uncertainties tend to increase with time and a more "stylised" approach may be required at later times, but do not explicitly allow a relaxation on the validation requirements for models/databases (Nagra, STUK).
- SSI/SKI state that the predictive content of assessments decreases with time, while illustration and stylised examples are used to a greater extent as time increases – most stringent approach needed for first 103 years according to SSI regulation – simpler and more robust modelling later on (see also observations from responses to Question 2.3).
- Regulations may allow the use of conservative assumptions to deal with uncertainties (e.g. for a set of a priori selected scenarios, AVN) – implying greater conservatism over longer timescales (Nagra).
- Regulations may recognise that in the very long term, irreducible uncertainties provide a natural limit to the timescale over which it is sensible to attempt to make detailed calculations of disposal system performance (Nirex). Near field and geosphere modelling are in general regarded to be unreliable once geological stability is no longer assured.

Treatment of transient processes occurring at different times and extending over different timescales (Question 7.3)

- There are generally no detailed regulatory requirements specific to transient processes (Hungary, Czech Republic, Canada, Belgium, and France).
- US EPA requires FEPs above a certain probability to be considered, whether they are transient or not.
- It is considered as unreasonable to require in regulation that all transient processes should be fully represented in safety assessment – it is a matter for the implementer to justify their treatment according to potential importance (SKI/SSI).
- Where transient processes are treated in a simplified manner (e.g. neglecting coupling processes), the justification must be given (IRSN).
- Different approaches may be used to treat transient processes (examples in Table A4.3).

Table A4.3: **Approaches used in safety assessment for the treatment of the transient process of near-field resaturation (examples from Nagra)**

Treatment in modelling system performance	Justification
***Reference assumption for spent fuel/high-level waste*:** Included in simplified manner – complete resaturation assumed by the time of canister breaching and start of release	Supported by independent, stand-alone calculations of resaturation times.
***Reference assumption for intermediate-level waste*:** Included in simplified manner – releases first occur at a time when some resaturation will have occurred. Thereafter, complete resaturation assumed.	Scoping calculations indicate significant resaturation will typically require a few hundred years. First releases conservatively assumed at 100 years. Conservative to assume complete resaturation thereafter.
***Alternative assumption*:** More detailed modelling of near-field resaturation for gas pathway analyses, but simplifying assumptions still applied.	Saturation state of near field has direct impact on the "storage volume" for repository-generated gas, and so must be included explicitly in analyses.

- Many programmes distinguish between (i) analyses of system development – detailed modelling to develop process understanding, often with explicit treatment of transients in all relevant time frames (e.g. THM evolution of near field, chemical evolution of porewater, degradation of seals) – and (ii) analyses of radionuclide transport – often with simplified models (e.g. with transient effects treated in a simplified manner using constant but conservatively selected parameters, alternative cases covering the range of future states, step-wise changes in system properties, etc.) based on the results of process modelling (Enresa, IRSN/Andra, Nagra, ONDRAF/NIRAS, NUMO/JNC).
- In some cases, transient processes can be omitted from assessment modelling because they are expected to be substantially complete before radionuclide release and transport take place (i.e. prior canister failure – see, e.g. Table A4.1) – but process modelling – e.g. of processes leading to canister failure – is required to confirm this.
- In other cases, transient processes in the initial period after emplacement may be very important – and complex because of THMC coupling (e.g. US DOE on thermal effects on flow through the waste emplacement zone of the repository and on canister integrity in Yucca Mountain case).
- Transient considerations may need to be taken into account from the very beginning of the construction period of a repository mine due to transient properties such as the varying convergence rate with time in the case of a repository in salt (GRS-K).
- Some transient system properties may be modelled explicitly in analyses of radionuclide behaviour – e.g. variable gas production rate in models of gas scenarios (Nagra); evolution of

external conditions due to expected climate change (SKB, OPG); saturation of the repository and establishment of reducing conditions (OPG); evolution of dam permeability (BfS/GRSB).

- The decision as to whether to model transients explicitly depends on the effects of the transient process on overall system evolution, etc. (PURAM), the sufficiency of data and understanding (Nirex) and, in some cases, on code availability and (for probabilistic assessments) run times.
- Some transient processes are subject to considerable uncertainty – e.g. high-pH plume evolution, and are still under discussion/development in some programmes, but simplified treatment is often possible (Nagra).
- Transient processes that do not affect the multi-barrier system significantly (e.g. climate change) can be treated as (steady-state) variants on the reference case, or via stylised approaches (ONDRAF/NIRAS).
- Transient behaviour of aquifers can be treated via an instantaneous equilibrium approach because it is characterised by short time scales compared to variations in release from the geosphere (ONDRAF/NIRAS).
- An explicit coupling between thermal phenomena and transport of radionuclides is included if a suitable modelling tool is available and if coupling is judged to be important for early releases (e.g. "dysfunctional canister" case – Andra).
- Safety assessments for spent fuel/high-level waste repositories may need to be developed further in this area – e.g. effects of climate change on mechanical, hydrogeological and geochemical conditions in the rock (BfS/GRS-B).
- Significant climate change is sometimes modelled as different steady-climate scenarios persisting for all time, and sometimes as a simplified time-dependent climate, i.e. a series of steady states (US DOE) – see also "stylised approaches", below.

Role of stylised approaches in areas other than human intrusion and biosphere (Question 7.4)

- Stylised approaches are used in all aspects of safety assessment modelling, in that models are by necessity simplified representations of a future reality – some features, events and processes may be entirely omitted.
- In general, simplifications require careful justification in the case of near field and geosphere models – e.g. that they are conservative or have negligible impact on calculated consequences.
- More arbitrary stylised assumptions are sometimes made in "what-if?" type calculations of, e.g. seal failure, canister defects, occurrence of undetected features, etc. (AVN, IRSN), natural events beyond the period of geological stability (NUMO/JNC) – and can be useful for scoping consequences of poorly researched topics (Andra).
- Any calculations involving such assumptions must be carefully distinguished from those addressing the expected range of possibilities for the evolution of the engineered and geological barriers so as not to undermine arguments regarding their barrier role – note the fundamentally different roles that the engineered and geological barriers play compared to the biosphere – barriers *vs*. "measuring stick" (Nagra).
- Treatment of aquifer evolution can be subject to irreducible uncertainty – but can be treated via a stylised approach (ONDRAF/NIRAS).

- The assumption of constant geosphere parameters may sometimes be a “stylised approach” at very long timescales (AVN).
- Climate change is probably the long-term evolution scenario most effectively addressed by “stylisation”, since characteristics and duration of future climate states cannot be defined with the degree of certainty that may, for example, be required by the regulator – stylisation has to date involved modelling a sequence of rapid transitions between future climate states, using climate cycles based on past climate data without inclusion of uncertainty in the timing of climate changes (US DOE).
- Correlation between human lifestyle and climate change is generally not considered in detail (e.g. US DOE).
- It is conceivable that stylised models could have a role for, say, the evolution of the geosphere at very long times when stability can no longer be guaranteed, but only as the basis of supporting arguments, while the main argument should be based on the much reduced radiological toxicity of the waste (Nagra; subrosion scenario described by BfS/GRS-B).
- STUK states that long-term evolution of the geosphere should be based partly on site-specific features, and partly on a stylised approach.
- SKB states that stylised approaches could be used in other areas apart from biosphere and human intrusion, as long as they are “well motivated” – this is allowed by Swedish regulation for times > approx 105 years – i.e. the time after the next glaciations cycle (SKI/SSI).
- Nirex does not foresee a stylised approach at such time – rather, detailed modelling gives way to qualitative understanding.
- Expert judgement plays a role in deriving reasonable and defensible hypotheses for stylised approaches (Enresa).

Questionnaire Section 8: Uncertainty management

Regulatory requirements as a function of time regarding the treatment of uncertainties in safety assessment (Question 8.1)

- Some regulations require an estimate of the magnitude and consequences of uncertainties/variability; although conservative approaches are also allowed (e.g. France, Switzerland), they also require sensitivity analysis (Andra, Nagra).
- Technical guidance for uncertainty management is still under development in Germany (GRS-K), Belgium, Czech Republic, Japan, Spain and the United States. The methodology for the treatment of uncertainty should derive from exchanges between implementers and regulators (AVN). In the United States, the uncertainty management approach is under continuous external and internal review as it is applied, and is augmented as needed in the US Yucca Mountain programme.
- Some regulations distinguish between scenario, model and parameter uncertainties.
- US EPA requires “levels of proof” inherent in the “reasonable expectation” approach to discourage reliance on extreme scenarios or parameter distributions as a way to “bound” uncertainties – allows the necessary flexibility to account for the inherently greater uncertainties in making long-term projections of performance.
- The use of a probabilistic approach is required (or implied) by some regulations (e.g. United Kingdom, United States, Sweden).

- US EPA standards require the individual protection standard to be addressed using probabilistic assessments, with the mean of the resulting dose distribution specified as a performance measure for the first 104 years after closure (the proposed revision to the standard requires the use of the median at times greater than 104 years to avoid undue influence from unlikely parameter-combination realisations with extremely high or low outcomes).
- Some regulations have an explicit requirement to consider alternative conceptual models (US NRC).
- Some regulations have an explicit requirement for complementary discussions on the significance of uncertainties that cannot be assessed quantitatively (STUK).
- The uncertainty surrounding human intrusion may be handled by specifying in regulation that it will occur at the earliest time possible and specifying a stylised analysis to serve as a test of repository resilience (US EPA).
- In Finland, the implementer need not address biosphere uncertainties after a few thousands of years – use of geosphere-biosphere flux constraints is instead defined in regulations (STUK).
- Effects of uncertainties are sometimes required by regulation to be investigated more thoroughly in earlier time frames (< 104 years – Hungary).
- In most cases, none of these requirements vary as a function of the time under consideration – even though many uncertainties tend to increase with time. In the case of the US, screening to determine the exclusion/inclusion of features, events and processes prior to 104 years is expected to serve as the basis for the assessment of performance up to a million years.

Main uncertainties affecting the performance of each major system component as a function of time or in different time frames (Question 8.2a)

- See also observations from responses to Question 6.2a.
- Some regulators acknowledge that it is up to the implementer to judge what the main uncertainties are (SKI/SSI, US NRC, and AVN).
- Box A4-2 gives examples of some of the main types of uncertainty in the "Dossier 2001" report of Andra.
- Many organisations have defined types of uncertainties affecting their systems as a function of time or in different time frames (see e.g. Box A4.2 below and Tables 5.2 & 5.3 in main text).

Box A4.2: **Examples of types of uncertainties treated in Andra's "Dossier 2001 Argile" and the later "Dossier 2005 Argile"**

1. *Homogeneity of the host formation and the possible presence of undetected heterogeneities*. In the framework of the "Dossier 2005 Argile", Andra produced a document explaining what strategy it could develop to identify and treat heterogeneities while building the repository, as a complement to surface and URL investigations. In parallel, a programme of investigations from the surface, using deviated boreholes, gave additional evidence of the good homogeneity of the formation. Clearly, this type of uncertainty is not time-dependent, though the way it could be

managed (through the initial choice of the host formation, surface investigation, inside the URL, while building the repository) lasts during different phases of the project.

2. *Geomorphologic evolution of the site.* At the stage of "Dossier 2001", no evaluation was performed of the interactions between climate change, erosion, and the possible changes in local hydrogeology. A "stylised" approach was used, assuming that the present conditions would prevail in the future. A preliminary hydro-geological model was determined, based on the results of site characterization. For "Dossier 2005", two hydro-geological models are defined, one representative of present conditions that has been re-defined using more recent data for the site, and one that takes into account a pessimistic evaluation of valley erosion and hydrographical changes over the next million years. Both are used in safety analyses. The second one is the reference model for phenomena occurring in the long run (such as radioactive releases from the host rock under the reference evolution scenario), the first one is used for sensitivity calculations or to evaluate early impacts, such as in case of human intrusion 500 years after closure. However, this type of uncertainty does not affect directly safety functions, and is only relevant when considering dose calculations.

3. *Geomechanical evolution.* With no direct evaluation of EDZ in representative conditions at that time, pessimistic evaluations were performed for Dossier 2001, taking into account two different timeframes. It distinguished between the immediate formation of EDZ, which was evaluated under very conservatives assumptions (assuming no mechanical containment of the host rock) and its later evolution, were no evolution of the EDZ – either favourable or not – was taken into account, assuming the backfilling of the repository would impede further damage and neglecting possibilities of self-sealing. These evaluations have been revised in the perspective of "Dossier 2005". In 2001, it was judged to be an important subject in the perspective of "Dossier 2005", due to the importance of EDZ in case of sealing defects. It led, in particular, to a revision of the technology for sealing the repository.

- Consequences are generally dominated by engineered barrier uncertainties at early times, while at later times uncertainties in the natural system become important (US DOE). Treatment in safety assessment includes calculations of alternative assessment cases/scenarios (probabilistic or deterministic), conservative simplification, stylised approaches, etc. (Andra).
- US DOE distinguishes aleatory (irreducible/stochastic) uncertainty and epistemic uncertainty, of which there are three categories – parameter uncertainty, alternative conceptual model uncertainty and abstraction uncertainty. For Yucca Mountain, the most important aleatory uncertainty is the initiating event probability uncertainty – which can lead to the assessment requiring submodels specific to the occurrence of the event (US DOE).
- ONDRAF/NIRAS distinguishes treatment of severe perturbations (altered evolution scenarios), other perturbations (variant scenarios), conceptual model uncertainty (treated using alternative models) and parameter uncertainty (treated using stochastic calculations).
- Treatment of uncertainty does not generally change as a function of time, except in as much that calculations may be terminated, or alternative safety indicators/arguments employed as a result of increasing uncertainty affecting model assumptions/databases, sometimes at the request or guidance of the regulator. Sensitivity analyses are used to identify most important uncertainties in particular time frames (ERAM example of BfS/GRS-B, Andra).
- In practice, uncertainties in, say, geosphere evolution (time dependent) are often translated to geosphere parameter uncertainty (time independent) – this needs careful justification (AVN, Nirex).

- In the United Kingdom, the approach of lumping together of uncertainty, variability and time-dependent effects and representing them, for the purposes of probabilistic calculations, as a single PDF has been challenged by some stakeholders – a more sophisticated treatment is being considered for the future (Nirex).

Impact (if any) of uncertainties on the overall safety provided by the system (Question 8.2b)

- This is a misleading question – uncertainties affect only the evaluation of safety – not safety per se (US DOE).
- Generally, safety cases aim to show that none of the identified uncertainties led to unacceptable adverse consequences – i.e. dose/risk remains below regulatory guideline.
- Many uncertainties affecting only one barrier or safety function typically have only a small effect on overall performance (Enresa) – this is a consequence of the multi-barrier principle, often required by regulation.
- Adding extra barriers may improve performance or isolation capability, but may increase the overall uncertainty in performance (US EPA).
- Greatest impact is from uncertainties impacting adversely on all safety barriers (e.g. borehole penetration into repository – Nagra) – in other cases the principle of multiple complementary safety functions mitigates impact.
- Uncertainties may lead to ranges of calculated dose maxima spanning several orders of magnitude – this may be acceptable provided criteria are still satisfied (NUMO/JNC).
- If problematic uncertainties are identified and these are not amenable to reduction by R&D, site characterisation, etc., then design modifications may be needed or, in extreme cases, the site itself may need to be reconsidered (IRSN).
- Example of mitigating uncertainty – titanium drip shield at Yucca Mountain – mitigates uncertainties related to water flow pathways within the repository and corrosion of the waste packages (US DOE).
- For repositories in clay, only uncertainties affecting the host rock have a significant impact on overall dose/risk, because of the highly effective transport barrier that it provides – uncertainties that are limited in their impact to the repository near field have a negligible overall impact (Andra – discussion of EDZ, Nagra, Enresa and ONDRAF/NIRAS).

Questionnaire Section 9: Safety indicators and the development of arguments for safety

Appropriate or most emphasised safety indicators in different time frames (Question 9.1a)

- Current practice in many countries largely follows recommendations of the EC SPIN project.
- Dose/risk generally provide the primary safety indicators for earlier times since these have the most direct relationship to human safety and assumptions underlying their calculations can be justified.
- Proposed US EPA regulations for Yucca Mountain specify (i), individual protection standard (dose from repository system not disturbed by human intrusion for 104 years and 106 years), (ii) the human intrusion standard (also dose for 104 years and 106 years) and (iii),

the groundwater protection standard – levels of radioactivity in a representative volume of groundwater (for 104 years in the proposed revised standard) (US EPA).

- Dose and risk are sometimes applied as the main safety indicators throughout the assessment period (SKB, Nagra) – but cannot be assessed exactly for long time frames (SKI/SSI).
- Risk alone may be judged inadequate in some countries – need to separate dose in a particular case and its probability of occurrence (AVN).
- (High) hazard potential of the waste (radiotoxicity) may also be emphasised at earlier times, as the basis of a requirement for a period of complete containment (as well as the need to allow for the thermal phase to pass) (e.g. France, Swiss regulations – see observations from responses to Question 2.1.).
- Other safety indicators, such as radionuclide concentrations and fluxes, are used in a complementary fashion, with comparisons made with naturally occurring values – this is sometimes required by regulation (e.g. German Draft Criteria – GRS-K, Finland – STUK).
- Indicators such as transport time through the geosphere do not give direct information about safety (no “safety measures”), but can be used to compare relative performance of sites/concepts, etc.
- Some maintain that dose/risk calculations are justified for as long as the multi-barrier system (esp. the natural barrier) is broadly predictable (e.g. ONDRAF/NIRAS).
- In some cases, various safety indicators are used in parallel throughout the assessment period (up to some cut-off time for quantitative evaluation) (e.g. Enresa, Nagra, OPG, NUMO/JNC), or at times when “predictions” of dose/risk are not possible (> 103 years in SKI’s regulations).
- In some cases, fluxes/concentrations between or within different parts of the system or within soils or near-surface groundwaters may be emphasised when uncertainties in the broad characteristics of the biosphere and human lifestyles (required for dose/risk calculations) become large – (in particular, during the next ice age 50 000 to 100 000 years from now – see STUK regulations).
- The value of the information (or appropriateness) provided by these safety indicators vary significantly in accordance with the timescale and the scenario considered (AVN).
- Concentrations in near-surface aquifers require information/assumptions regarding the dilution potential of the aquifers, which also becomes uncertain at sufficiently long times – the flux to the aquifer may be more emphasised as a safety indicator at these times.
- Strongly decreased hazard potential of waste due to decay may be emphasised at very distant times – e.g. indicates significantly reduced hazard by the time the stability of the geosphere can no longer be assured (Switzerland, German Draft Criteria – 106 years, UK).
- OPG considering use of alternative safety indicators for chemical toxicity for very long times (> 106 years), since chemically toxic species do not decay.

Measures or protection criteria against which safety indicators can be compared (Question 9.1b)

- Risk is the underlying basis of most measures – risk limit is judged according to its acceptability to society, although measures themselves may refer to dose, concentration, etc. (e.g. US EPA).

- Dose and/or risk are indicators of compliance set by regulation in most countries.
- Application of different measures for different time frames should not be interpreted as providing less safety or protection to future generations.
- In proposed revisions to US regulations (see Appendix 3) constraints on dose are different for the periods before and beyond 104 years in recognition of increased uncertainty over time.
- Dose/risk limits are based on a range of arguments; including ICRP recommendations for single sources (e.g. SKI/SSI).
- Measures for other safety indicators are generally left for the implementer to determine/justify, the exception being Finnish regulations, where geosphere-biosphere flux constraints are specified in regulations, on the basis of stylised biosphere scenarios and a dose criterion of 0.1 mSv per year and some comparisons with natural radioactive fluxes.
- These measures (unlike dose/risk) may be related to the specific site under consideration (NUMO/JNC).
- Radiotoxicity of waste can be compared to that of natural radionuclides in a given volume of host rock (Nagra) or that of a volume of natural uranium corresponding to the volume of rock removed in the excavation of the repository tunnels (Nagra, Nirex).
- Such comparisons may be open to criticism because isotopic composition of spent fuel differs from natural uranium – many fission products are more mobile than actinides (Enresa; see also SKI/SSI response to Question 2.2).
- Andra mentions that it no longer makes such comparisons, since they are judged not to be very convincing from the stakeholder point of view.
- Radiotoxicity fluxes between host rock and confining units can be compared to fluxes in e.g. biosphere aquifers and rivers close to the site (Nagra; BfS/GRS-B) or the rate of release of radiotoxicity due to the erosion of the reference biosphere area (Nagra).
- Radiotoxicity concentration in aquifer – compared to that of potable natural waters (BfS/GRS-B, NUMO/JNC).
- Note that radiotoxicity flux as an indicator compared to reference values derived from natural concentrations and flowrates does not provide any added value compared to radiotoxicity concentrations (ENRESA).
- Natural concentrations provide references for comparison at long time frames – not necessarily applied as limits (SKI/SSI response to 2.2).
- Regulatory concentration limits for routine releases from existing nuclear facilities – derived from annual limits for intake – can be used to derive a common scale for all radionuclides of concern, including those not naturally present in the environment (NUMO/JNC).
- Where comparison is made with natural systems, there is a need to consider the assumption that nature in general is radiologically safe (AVN).
- Validity/meaning of comparisons with natural systems needs to be addressed through open discussions between implements, regulators and other stakeholders (ONDRAF/NIRAS).

Initial period when no release from parts of the system or the system as a whole is expected (Question 9.2)

- Not generally defined in regulatory requirements (see, however, French safety rule and Swiss regulations – response to 2.1).
- Nirex assumed no release from intermediate-level waste/low-level waste packages via the groundwater pathway for a few hundred years – reality may be much longer; release of radioactive gases (and radionuclides conveyed as volatiles by bulk gasses) may occur sooner, although they may take some years to reach the surface.
- Nagra – for intermediate-level waste/low-level waste – some waste containers may be fitted with gas vents – in some assessments, no credit is taken for complete containment by intermediate-level waste/low-level waste containers (e.g. Nagra, OPG).
- The repository remains unsaturated for a period (~500 years – Nagra), or the void volumes of the repository will not be completely flooded, i.e. flow is directed into the repository, for a period of 3 000 years for unsealed mine openings, 19 000 to > 106 years for sealed mine openings and zero releases may occur while water flow is directed inwards (ERAM, BfS/GRS-B).
- Uncertainties sometimes mean that this period is either disregarded (ERAM/ unsealed mine openings), or credit is taken for zero release over a much shorter period (100 years, Nagra).
- For a spent fuel/high-level waste repository in rock salt, once the salt reaches its "target state", the expected situation is zero release for as long as prognoses of geological evolution can be made (GRS-K).
- In other cases, for spent fuel/high-level waste, zero release will occur as long as complete containment is provided by canisters/overpacks (see Table 3.2 in main text).
- In the cases of, for example, NUMO/JNC and Nagra, the containment period is not critical for ensuring safety – rather, it simplifies the analysis and provides clear/accessible safety arguments for the period that may be of particular concern to the public.
- The QA programme for canister fabrication and the modelling of corrosion and mechanical phenomena that could impair canister integrity are used to substantiate the expected lifetimes of containers (SKB, NUMO/JNC).
- The possibility of one or several defective canisters/waste packages giving early releases is also considered in many assessments (e.g. Nagra, SKB).
- In the US case, for defective canisters, no water contacts the waste as long as the temperature inside the packages is above boiling – < 100 years for some vitrified high-level waste packages (US DOE).
- Finnish regulations state that releases to the host rock should be "effectively hindered" for several thousands of years.

Contribution of natural analogues to the understanding of slow processes operating over long timescales and justification for more widespread use of such analogues (Question 9.3)

- Consensus is that analogues have contributed significantly to understanding of slow process, but quantitative information that can be used directly in safety assessments is limited due to uncertainties in the interpretation of analogues.
- Several "materials" analogues exist (uranium, copper, iron, bentonite, cement, etc.).
- Specific examples given in the responses:

  - For the spent fuel matrix – slow dissolution and absence of significant radiolysis effects (Nagra) – likely oxidation products in an unsaturated tuff setting (US DOE).
  - For the vitrified high-level waste matrix – slow dissolution (Andra, Nagra, ONDRAF/NIRAS, NUMO/JNC).
  - For steel corrosion (anthropogenic analogues) – Andra, Enresa, Nirex, NUMO/JNC – steels in concrete environment – ONDRAF/NIRAS).
  - For copper as a canister material – low corrosion rates (Nagra).
  - For cement degradation (NUMO/JNC).
  - For bentonite – limited thermal alteration (Andra, Nagra, NUMO/JNC); retention of swelling properties and plasticity if alteration occurs; low permeability; sorption (Nagra); stability over times for up to 10^8 years in saturated and dry conditions (SKB).
  - For geosphere stability for periods well in excess of a million years (SKB).
  - For clay host rocks – alkaline perturbations (Andra/IRSN), isotopic profiles to show immobilisation/slow transport (Andra, ONDRAF/NIRAS);
  - For fractured hard rocks – existence of matrix diffusion (Enresa).
  - For rock salt – examples include: long-term geoscientific prognosis (e.g. observations of other salt domes – GRS-K); behaviour of salt in the presence of heat sources (basalt intrusions – GRS-K); isolation potential (presence of brine inclusions and bromide concentration profiles – GRS-K).
  - For long-term climate evolution (e.g. Devil's Hole calcite core) (US NRC).
  - Analogues elsewhere of possible future climate conditions at a site – e.g. tundra (Nirex).

- For engineered barrier systems – arguments derived from analogues are often indirect/supplementary – "confidence building" arguments – difficulties in interpretation are due to uncertainties in boundary conditions and in evolution over long time scales in the past.
- Analogues also provide a general argument to support the basic concept of geological disposal (long-term survival of ore bodies, etc.) – e.g. Nirex.
- Judgement of (overall) safety based on a range of complementary considerations, including natural analogues (Finnish regulations) – may be particularly important beyond say 106 years, where quantitative evaluations of releases etc. cannot be well supported.
- Some feeling that more widespread use would be justified (BfS/GRS-B, Nirex, SKI/SSI, US DOE, and OPG).

QUESTIONNAIRE SECTION 10: Developing and presenting the safety case

Addressing issues associated with timescales, e.g. in a dedicated section of a safety report (Question 10.1)

- Generally, this is not the practice – timescales emerge naturally from the discussion of specific events/processes, safety functions and the couplings between processes – the specific issue of the overall time frame of concern/the cut-off time for calculations is sometimes addressed in a specific section (e.g. Nagra); timescales in a general sense are discussed in a dedicated section of SKB's latest assessment report.
- The Japanese H12 safety assessment contained sections on "supplementary safety indicators" and "reliability of the safety assessment" – including support from analogues.

- A discussion on timescales and what they mean to the safety case should provide context for the safety case, wherever it is placed (US DOE) – could be useful for readability, transparency, traceability of argumentation etc. (AVN).
- Uncertainty is the primary issue associated with timescales – regulator needs to know how uncertainties are handled – may be effective to communicate this information in a dedicated section of a safety report or licence application (US EPA).
- Timescales are a central element to consider in the discussion of scientific understanding, scenarios, models, data, impact, etc.
- In the proposed Nirex time frames approach, it is envisaged that a report section covering each time frame will be presented.
- STUK suggests a section of the safety report discussing different time frames in turn (risks, safety features, methods used) would be valuable – including time frames not mentioned in regulations, but may be of interest to non-specialist audiences (0-500 years, say).
- SKI/SSI suggest that a background report covering the expected evolution of the site and how uncertainties are dealt with in different time frames could be useful.
- For wider (non-specialist) audiences, a dedicated section placing the timescales of radioactive decay and system evolution in perspective (with examples from nature and history) could be useful (GRS-K).
- "Timescales" could be seen as a structuring element of the different sections of a safety case: in all the main sections of a safety report, a discussion of scientific basis, scenarios, models and data, impact calculations and results, treatment of uncertainty etc. in different time frames is a central element to consider (ONDRAF/NIRAS).
- OPG suggests sections dealing with the overall time frame for the assessment, major uncertainties as a function of time and their treatment, and general time-related modelling issues such as assumptions of steady-state conditions or static critical group.

Emphasis on different time frames when presenting a safety report, e.g. for regulatory review (Question 10.2a)

- Emphasis on certain time frames can be directed by regulations, which in turn reflect a complex, public consideration of ethical issues, practical issues and societal values (US DOE).
- Regulatory principles may require, or the implementer may choose to justify (e.g. on the basis of hazard potential) more detailed analysis in certain time frames.
- Although the time frames emphasised may not be viewed as "more important" (intergeneration equity) there will clearly be more to say about the period covered by detailed analyses.
- In the US, it has been proposed that the 104 years projections would be subject to a different constraint than the longer-term projections (US EPA).
- Different lines of argument may be more appropriate in different time frames (e.g. Nirex).
- The safety case may emphasise some barriers or safety functions over others – timescales of events and processes affecting these barriers may determine time frames emphasised in a safety report – e.g. a safety case emphasising containment by engineered barriers might have more to say about earlier time frames US EPA).

- SSI's regulations require a dedicated account of the first 103 years – possibly in part for the reason cited above.
- Addressing only a single (106 years) time frame arguably gives too little attention to early periods (Nirex).
- By presenting each time frame explicitly, each audience will be able to focus on its area of interest (Nirex).

Emphasis on different time frames when presenting a safety case or the findings of a safety assessment to a wider, non-specialist audience (Question 10.2b)

- Same basic arguments/information base for all audiences in order to preserve credibility (Nagra).
- Credibility of the assessment as a whole must be shown – general public may be particularly sceptical about long-term evaluation – especially if they are understood as exact "predictions" (Andra).
- The public is highly diverse (US EPA).
- When presenting to the public (as with any audience) emphasis should be on performance relative to regulatory standards – but uncertainties must be acknowledged (US EPA).
- The experience of the Konrad public hearing shows, that on one hand, a rather general concern exists about the credibility of assessments as a whole and on the other hand, very specific concerns exist about issues in the (very) short term, e.g. loss of property value, disturbance by waste transportations, safety of the present and the next one or two generations (GRS-K).
- Level of explanation of arguments/focus on specific time frame can be adapted to the specific needs and demands of the audience.
- Time frames can be useful in communicating with a technical audience – providing an easier disaggregation and discussion of findings. It appears, however, that distinguishing between timeframes in the general conclusions of a safety case is not always easy, as safety is judged globally (Andra).
- The operational phase and the immediate post-closure phase may be of particular interest to the wider public, and must not be neglected in presentations (Andra).
- STUK/SKB – first 1 000 years could be stressed when presenting to the public – high activity but high confidence in disposal system – tends not to be emphasised among experts since more difficult safety issues generally concern longer timescales.
- May need greater emphasis on zero releases while canisters remain intact (Enresa, PURAM).
- Long-term stability of host formation may be of public concern (ONDRAF/NIRAS).
- Natural analogues can be useful in addressing such concerns (US EPA/US DOE).
- Low probability/consequences and/or late timing of alternative evolutions may need to be emphasised – especially if these are of particular public interest – e.g. earthquakes, climate change.

- Useful to provide context by discussing timescales in relation to familiar time periods (e.g. recorded human history – a few thousand years) (US EPA).

Views of organisations on the need for further development or regulatory guidance on the presentation and communication of the results of safety assessments in various time frames (Question 10.3)

- Limited possibilities for regulatory guidance since timescales are site/concept/strategy dependent (Andra).
- Issue should be dealt with in consultations between regulators and implementers, considering future safety assessments and their reviews (SKI/SSI).
- Over-prescriptive guidance not practicable or helpful (Nirex).
- Guidance can be useful regarding the use of different safety indicators in different time frames, especially where "technical" arguments to support this use are not available (Andra, NUMO/JNC).
- Regulatory guidance useful on the use of safety assessment results beyond the time frame when geosphere stability can be assured (NUMO/JNC).
- After what time should calculations stop? Are dose curves beyond 106 years useful or meaningful? Do they undermine stakeholder confidence? Need to clarify acceptability (to regulators) of arguments based on reduced radiotoxicity of wastes (ONDRAF/NIRAS, Nagra).
- Communication with the public/non-technical audience – arguments to explain safety in different time frames and possible need for emphasis on early times – may be more a matter for the implementer than the regulator, but could benefit from further development (Nagra, GRS-K, US EPA).

Need to be able to explain why it may be acceptable to move forward with a programme even when some significant uncertainties are unresolved – guidance in the forms of successful examples of communication from national programmes would be helpful (US EPA).

- It is necessary to explain the rationale/motivation for including/excluding processes in different time frames (Andra).
- Need effective (and concise) ways to correctly show results, and place them into the proper context of what is known and what is uncertain (US DOE).
- Need guidance on how and when to deal with potential human intrusion (ONDRAF/NIRAS).

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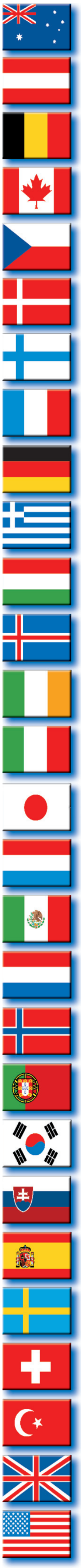

Considering Timescales in the Post-closure Safety of Geological Disposal of Radioactive Waste

A key challenge in the development of safety cases for the deep geological disposal of radioactive waste is handling the long time frame over which the radioactive waste remains hazardous. The intrinsic hazard of the waste decreases with time, but some hazard remains for extremely long periods. Safety cases for geological disposal typically address performance and protection for thousands to millions of years into the future. Over such periods, a wide range of events and processes operating over many different timescales may impact on a repository and its environment. Uncertainties in the predictability of such factors increase with time, making it increasingly difficult to provide definite assurances of a repository's performance and the protection it may provide over longer timescales. Timescales, the level of protection and the assurance of safety are all linked.

Approaches to handling timescales for the geological disposal of radioactive waste are influenced by ethical principles, the evolution of the hazard over time, uncertainties in the evolution of the disposal system (and how these uncertainties themselves evolve) and the stability and predictability of the geological environment. Conversely, the approach to handling timescales can affect aspects of repository planning and implementation including regulatory requirements, siting decisions, repository design, the development and presentation of safety cases and the planning of pre- and post-closure institutional controls such as monitoring requirements. This is an area still under discussion among NEA member countries. This report reviews the current status and ongoing discussions of this issue.

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