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PAMINA

Performance Assessment Methodologies in Application to Guide the Development of the Safety Case

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European Handbook of the state-of-the-art of safety assessments of geological repositories-Part 1

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Foreword

The work presented in this report was developed within the Integrated Project PAMINA: **P**erformance **A**ssessment **M**ethodologies **IN** **A**pplication to Guide the Development of the Safety Case. This project is part of the Sixth Framework Programme of the European Commission. It brings together 27 organisations from ten European countries and one EC Joint Research Centre in order to improve and harmonise methodologies and tools for demonstrating the safety of deep geological disposal of long-lived radioactive waste for different waste types, repository designs and geological environments. The results will be of interest to national waste management organisations, regulators and lay stakeholders.

The work is organised in four Research and Technology Development Components (RTDCs) and one additional component dealing with knowledge management and dissemination of knowledge:

- In RTDC 1 the aim is to evaluate the state of the art of methodologies and approaches needed for assessing the safety of deep geological disposal, on the basis of comprehensive review of international practice. This work includes the identification of any deficiencies in methods and tools.

- In RTDC 2 the aim is to establish a framework and methodology for the treatment of uncertainty during PA and safety case development. Guidance on, and examples of, good practice will be provided on the communication and treatment of different types of uncertainty, spatial variability, the development of probabilistic safety assessment tools, and techniques for sensitivity and uncertainty analysis.

- In RTDC 3 the aim is to develop methodologies and tools for integrated PA for various geological disposal concepts. This work includes the development of PA scenarios, of the PA approach to gas migration processes, of the PA approach to radionuclide source term modelling, and of safety and performance indicators.

- In RTDC 4 the aim is to conduct several benchmark exercises on specific processes, in which quantitative comparisons are made between approaches that rely on simplifying assumptions and models, and those that rely on complex models that take into account a more complete process conceptualization in space and time.

PAMINA reports can be downloaded from http://www.ip-pamina.eu.

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1. Introduction

Spent nuclear fuel and long-lived radioactive waste must be isolated from humans and the environment for many thousands of years, which require a safe and adequate waste management strategy. Disposal of spent nuclear fuel and long-lived radioactive waste in engineered facilities (repositories) located deep underground in suitable geological formations is the waste management strategy that is currently investigated in most countries. This strategy can provide long-term security and passive safety in a manner that does not require active monitoring, maintenance or institutional control.

Even though the basic approach towards geological disposal of long-lived radioactive waste and spent nuclear fuel is quite similar within the countries of the European Union and other countries with advanced disposal programmes, such as Switzerland, there are significant differences between countries.

A repository is considered to be safe if it meets the relevant safety standards that are recommended internationally or that are specified by the responsible national regulator. Within the European Union, however, there exist differences in the methodologies followed to demonstrate the safety of a repository. These differences are due to specific national regulations and the particular characteristics of the engineered barriers and the host formation selected.

The justification of the long term safety of a deep underground repository is a complex task due to the many different materials present, the great number of processes that can take place (and their couplings), the heterogeneity of the host formation and the large timescales that need to be considered in the safety assessment. Such complexity makes it difficult to demonstrate the safety of the repository exclusively via experiments, and requires the development of specific methods and tools.

Development of a safety assessment for disposal of radioactive waste involves consideration of the evolution of the waste and the engineered barrier system, and the interactions between these and, the often relatively complex, natural systems which are also evolving. The timescales that must be considered are much longer than the timescales that can be studied in the laboratory or during site characterisation. These and other factors lead to several types of uncertainty (e.g., on scenarios, models and processes, and parameters) that need to be taken into account when assessing the long-term performance of the disposal system.

Although a safety assessment was never merely a set of numerical calculations, the scope of this concept has widened in the last years to include the collation of a broad range of evidence and arguments that complement and support the reliability of the results of the quantitative analyses, giving place to the Safety Case concept. The safety case becomes more comprehensive and rigorous as a programme progresses and is a key input to decision making at several critical points in the repository planning and implementation process.

In recent decades, an enormous effort has been undertaken in EU Member states, and worldwide, to develop, test and implement methods required for the safety assessment of geological repositories of radioactive waste. As a consequence, a very large body of experience has been generated, which provides a firm basis for future steps in development programmes. In parallel with development activities, a growing number of formal evaluation processes, including regulatory processes, have been and are being carried out, generating useful guidance for future work.

The Integrated Project (IP) PAMINA (**P**erformance **A**ssessment **M**ethodologies **IN** **A**pplication to Guide the Development of the Safety Case) is part of the Sixth Framework Programme of the European Commission. The PAMINA Project started in October 2006 and lasted three years until September 2009. It brought together 26 organisations from ten European countries and one EC Joint Research Centre with the aim of improving and harmonising methodologies and tools for demonstrating the safety of deep geological disposal of long-lived radioactive waste for different waste types, repository designs and geological environments. The PAMINA Project was intended to generate results of interest to national waste management organisations, regulators and stakeholders.

The PAMINA Project was organised in four Research and Technology Development Components (RTDCs) and one additional component dealing with knowledge management and dissemination. The objective of the first of these components (RTDC-1) was to make a comprehensive review of the methodologies used by the different organisations to develop the safety case, culminating in development of this Handbook. The participating organisations are shown in Table 1.

The main objective of PAMINA RTDC-1 was to assess the state of the art of the methodologies and approaches used to develop the safety case of deep geological repositories by different European countries, and to distil the lessons learned from the rich experience accumulated in their development and application. More specifically, the safety assessment methodologies and the tools used have been reviewed, and the possible deficiencies in methods, tools and data have been identified. An exploration of a potential harmonisation of terminology has also been carried out.

The work in RTDC-1 covered eleven topics identified as necessary elements in any safety assessment (see Table 2). For each topic, a designated coordinator developed guidance on the scope and outstanding issues for that topic. Using these guidelines, each participating organisation provided a description of how the corresponding topic was considered or implemented in their country. The analysis of these contributions, made by the topic coordinator, was discussed in workshops aimed at reaching a consensus on critical issues after thorough review and discussion (3-4 topics were discussed per workshop). A task report was prepared for each topic based on the outcome of these workshops and the synthesis of the individual contributions. Chapters 4-14 of this Handbook contain the 11 task reports. The content of these chapters represents the fruit of the collaborative work by the organisations participating.

One of the key aspects of this work has been to bring together the different perspectives on each topic from waste management organisations responsible for developing the national disposal concept(s) and organisations responsible for evaluating the acceptability of such concepts. The goal was that each participating organisation would analyse each topic form its own perspective to provide a comprehensive understanding of the different aspects of the topic.

Table 1 - Organisations providing national contributions in support of this Handbook. (Developers are shown in white cells, and regulators and their technical support organisations are shown in shaded cells).

Acronym	Organisation	Country
Andra	Agence Nationale pour la Gestion des Déchets Radioactifs	France
BGR	Bundesanstalt für Goewissenschaften	Germany
DBETEC	DBE Technology GmbH	Germany
Enresa	Empresa Nacional de Residuos Radiactivos S.A.	Spain
FANC, Bel V (*)	Federaal Agentschap voor Nucleaire Controle / Agence Fédérale de Contrôle Nucléaire Bel V (Technical safety organization of FANC)	Belgium
GRS-B	Gesellschaft für Anlagen- und Reaktorsicherheit mbH (Braunschweig)	Germany
GRS-K	Gesellschaft für Anlagen- und Reaktorsicherheit mbH (Köln)	Germany
IRSN	Institute de Radioprotection et de Sureté Nucléaire	France
NDA	Nuclear Decommissioning Authority	United Kingdom
NRG	Nuclear Research & Consultancy Group	Netherlands
NRI RAWRA	Nuclear Research Institute Rez plc Radioactive Waste Repository Authority	Czech Republic
Posiva	Posiva Oy	Finland
SCK/CEN, ONDRAF/ NIRAS	Studiecentrum voor Kernenergie / Centre d'Etude de l'Energie Nucléaire Organisme National des Déchets Radioactifs et des Matières Fissiles Enrichies / Nationale Instelling voor Radioactief afval en verrijkte splijtstoffen	Belgium

(*)Bel V was AVN (Association Vinçotte Nuclear) at the beginning of the project.

Table 2 shows the contributions provided by each organisation to the different topics. In total, 114 contributions were produced, and are included as Appendices to the 11 task reports that make up PAMINA [Deliverables D1.1.1], [Deliverable D1.1.2] and [Deliverable D1.1.3].

Table 2 - Organisations that provided a written contribution to each topic.

Topic / Chapter / Organisation	Safety strategy (chapter 4)	Safety functions (chapter 5)	Safety and performance indicators (chapter 6)	Evolution of the system (chapter 7)	Scenarios (chapter 8)	Human intrusion (chapter 9)
Andra	X	X	X	X	X	X
DBETEC			X			
Enresa	X	X	X	X	X	X
FANC/AFCN Bel V	X	X	X		X	X
GRS-B			X	X		X
GRS-K	X	X	X	X	X	X
IRSN	X	X	X	X	X	(*)
NDA	X	X	X	X	X	X
NRG	X	X	X	X	X	X
NRI RAWRA	X	X	X	X	X	X
Posiva	X	X	X	X	X	X
SCK/CEN, ONDRAF/ NIRAS	X	X	X	X	X	X

Table 2 – continued.

Organisation \ Chapter \ Topic	Biosphere (chapter 10)	Modelling strategy (chapter 11)	Data selection (chapter 12)	Uncertainty management (chapter 13)	Sensitivity analysis (chapter 14)
Andra	X	X	X	X	X
BGR			X (**)		
DBETEC			X (**)		
Enresa	X	X	X	X	X
FANC/AFCN Bel V	X	X	X		
GRS-B	X	X	X	X	X
GRS-K	X	X	X (**)	X	X
IRSN		X	X	X	X
NDA	X	X	X	X	X
NRG	X	X	X	X	X
NRI RAWRA	X	X	X	X	X
Posiva	X	X	X	X	X
SCK/CEN, ONDRAF/ NIRAS	X	X	X	X	X

(*) IRSN contributed to the regulatory aspects in the Andra contribution.

(**) Joint contribution of GRS-B, DBETEC and BGR.

This European Handbook of the state-of-the-art of safety assessments of geological repositories is a central deliverable of PAMINA, and is a main building block for knowledge management and dissemination.

It is intended to be used by waste management organisations, and by regulators and their technical support organisations, as a reference book that can be exploited on a national level without prescribing any national standards. Furthermore, the Handbook is expected to be of interest to other stakeholders and the general scientific community.

The document starts with a description of the purpose of the Handbook and the process followed to create it (chapter 1). A brief description of the safety case concept and its role in the development of a safe disposal system is in chapter 2. Summaries of the national context for the different countries that contributed to the handbook are found in chapter 3. The stage of the national disposal programme has a strong effect on the degree of detail and methodologies use in the safety case. Chapters 4-14 are the core of the Handbook – as already noted, they contain the 11 task reports.

In addition to this Deliverable – which in fact forms Part 1 of the Handbook – we draw attention to a companion report, the PAMINA Project Summary Report [Deliverable D5.1], which summarises work carried out in the entire project. The work carried out in other RTDCs within PAMINA takes the state-of-the-art forward in specific areas, and the totality of that work represents Part 2 of the Handbook. All published PAMINA reports are available on the PAMINA Project website: http://www.ip-pamina.eu/publications/reports/index.html.

1.1 References

[Deliverable D1.1.1] Task Reports for the First Group of Topics: Safety Functions; Definition and Assessment of Scenarios; Uncertainty Management and Uncertainty Analysis; Safety Indicators and Performance/Function Indicators. J. Marivoet (SCK/CEN), J. Alonso (Enresa), T. Beuth and D.-A. Becker (GRS-B), 2008.

[Deliverable D1.1.2] Task Reports for the Second Group of Topics: Safety Strategy; Analysis of the Evolution of the Repository System; Modelling Strategy; Sensitivity Analysis. M. Capouet (ONDRAF/NIRAS), L. Griffault (Andra), J.L. Cormenzana (Enresa), D.A. Becker (GRS-B), 2009.

[Deliverable D1.1.3] Task Reports for the Third Group of Topics: Human Intrusion, Biosphere and Criteria for Input and Data Selection. D.A. Galson and R.A. Klos (GSL), C. Serres and G. Mathieu (IRSN), T. Beuth (GRS-B), J.L. Cormenzana (Enresa)

[Deliverable D5.1] Project Summary Report. D.A. Galson and P.J. Richardson (GSL), 2011.

[Milestone M1.2.1] The Treatment of Uncertainty in Performance Assessment and Safety Case Development: State-of-the-Art Overview. D.A. Galson and A. Khursheed (GSL), 2007.

2. Safety Case overview

The OECD-NEA defines a long-term safety case for a geological radioactive waste repository as follows:

"A safety case is the synthesis of evidence, analyses and arguments that quantify and substantiate a claim that the repository will be safe after closure and beyond the time when active control of the facility can be relied upon." [NEA, 2004].

It is recognised that the safety case is more than the calculated numerical results for safety indicators, it presents the underlying evidence, processes and methodologies that build confidence in the quality of the science and institutional processes as well as in the results of the analyses. The safety case for a geological radioactive waste repository will be based on an understanding of the evolution and performance of the engineered barriers that contain the waste and the geological environment that isolates the waste from the human environment.

2.1 Role of the Safety Case

A safety case is generally produced by the implementing agency that is designing and constructing the repository. Typically, a series of safety cases will be produced, at key stages in a stepwise repository development programme, generally to support decisions to move to the next stage of the programme. For example, in the early stages, a generic safety case may be developed to support decisions on the choice of disposal concept and siting strategy. Once a site or sites have been identified for investigation, site-specific safety cases will be developed to support planning applications for site investigation activities. The safety case will be further developed during the site evaluation stage, taking account of new data and understanding from the on-going research and site investigation work.

The main purpose of each safety case will therefore depend on the context in which it is produced, and this may also affect the primary audience for the safety case.

In the early, generic stages, a safety case is likely to focus upon demonstrating the feasibility of proposed disposal concept options (and possibly even waste management options other than geological disposal). Such safety cases are likely to focus on demonstrating an understanding of the key processes affecting the safety of a repository, and likely to rely more on qualitative than quantitative safety arguments and analyses. The main audiences for the safety case at this stage are likely to be those responsible for setting or influencing national policy. If a volunteer approach to site selection is being followed, the safety case is also likely to be of interest to members of communities that may be considering volunteering.

As the repository development programme progresses to the siting strategy stage, the focus of the safety case is likely to become developing the methodology and evaluation criteria for undertaking site assessments and to assist in identifying site discriminating factors. An important aspect of the safety case at this stage is likely to be explaining how the safety case and its analyses will be used for site evaluation within the repository development programme.

During site evaluation, both local communities and regulatory and planning organisations are likely to be key audiences for the safety case. There may also be considerable attention from Non-Governmental Organisations and the media as decisions are taken over the siting of a radioactive waste repository. The assessment approach at this stage will be strongly influenced by the applicable national regulations, as the safety case will be seeking to demonstrate whether it is likely that the regulatory requirements would be met to enable a repository to be licensed at the site(s) under consideration.

When the repository programme progresses to more detailed site investigations, it is likely that the implementing agency will produce a series of iterative safety cases and/or updates to safety cases. These safety cases will become increasingly detailed as they assimilate more information from the underpinning research programmes. The aim between successive iterations is to reduce the significant uncertainties and thus increase confidence in the safety case. The safety case that is eventually prepared for regulatory submission is likely to be a substantial set of documents, explaining and justifying understanding of the repository system, including the performance of the engineered barriers and geological environment over long timescales. The timescales for the safety assessment may be prescribed in the regulations, or may need to be justified by the implementing agency, but are likely to run to hundreds of thousands of years.

Figure 1, which is reproduced from [Nirex, 2005], summarises how the focus and audiences for a safety case may evolve throughout a stepwise repository development programme. The gradual shading on this diagram is used to indicate that aspects of the stages may merge into one another, there is no sudden change in approach, rather an evolution with increasing definition of the programme. The stakeholders who will be most influential in making the decisions at each stage will change as the programme progresses, in line with the changing focus of the dialogue and technical work. This has implications for the assessment approach, the level of safety analysis, and how the safety case is presented. At each stage, the safety case provides a platform for informed discussions among experts and with stakeholders on the current level of confidence in the repository project, and can be used to identify any issues where further work is required.

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 makers	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 & 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, systematic 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.

Figure 1 - Evolving context of the Safety Case (from [Nirex, 2005]).

2.2 Key elements of a Safety Case

Although, as discussed above, safety cases may evolve throughout a stepwise repository development programme, there are some essential elements that are common to almost all safety cases. The OECD-NEA, has defined the following key elements of a safety case, as summarised in Figure 2 [NEA, 2004]:

- A clear **statement of purpose**, to provide the context for the safety case.
- The **safety strategy** – the high-level approach to achieving safe disposal, which includes the overall management strategy, a siting and design strategy and an assessment strategy.
- The **assessment basis** – which is the collection of information and tools supporting the safety assessment. The assessment basis includes an overall description of the repository and its geological setting, relevant technical data and scientific understanding, the range of scenarios to be addressed and the methods, models, computer codes and databases to analyse the repository system performance.
- The **evidence, analyses and arguments for safety** – this includes the results of numerical calculations, typically compared against safety criteria, and also more qualitative arguments providing additional context or support.

- The **synthesis** of the above evidence – which upheld by the quality of the assessment basis, supports a statement of the confidence in the safety case.

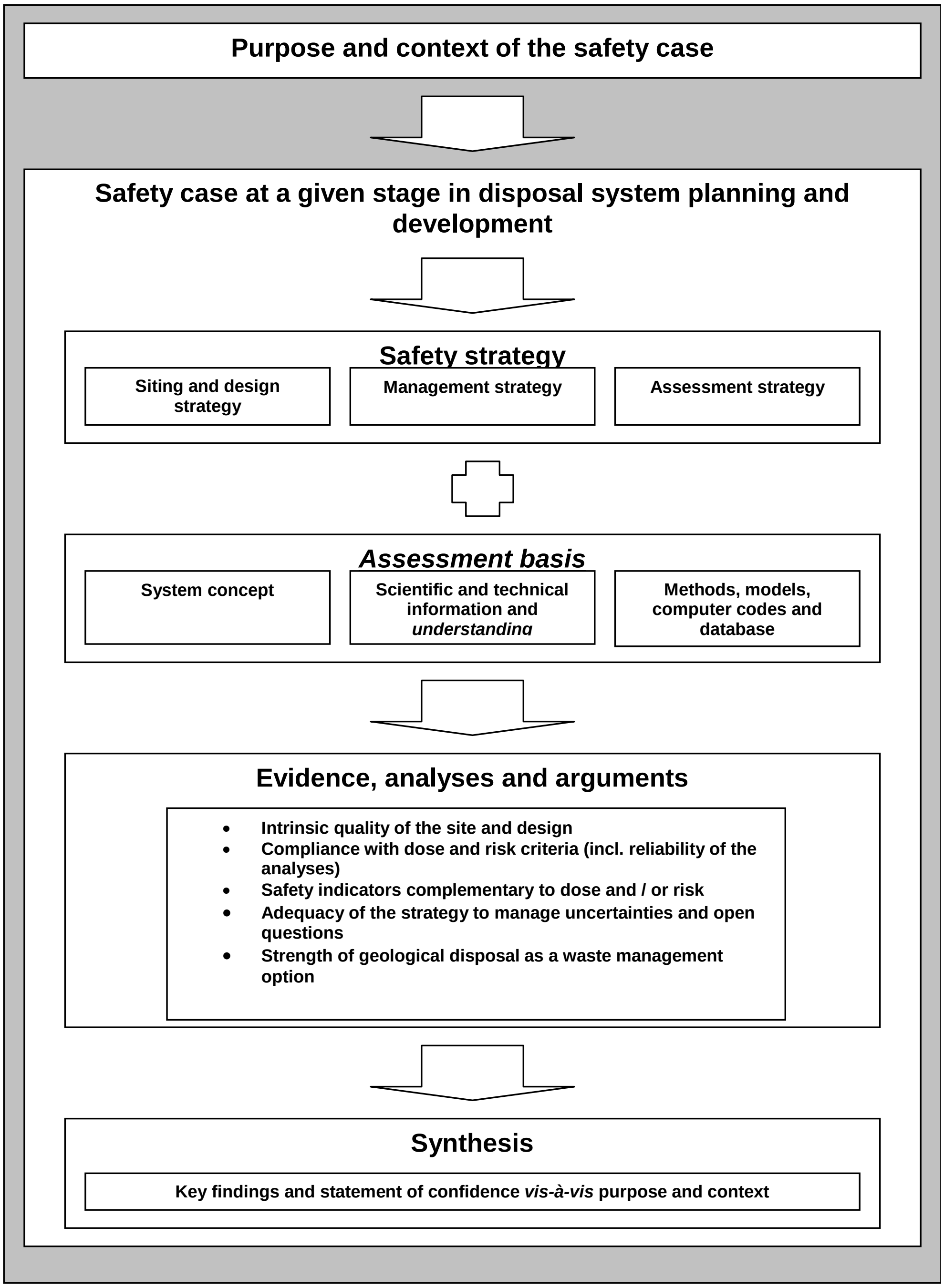

Figure 2 - An overview of the relationship between the different elements of a Safety Case (from [NEA, 2004]).

The PAMINA Project has addressed topics that are relevant to the safety assessment aspects of the safety case. The safety assessment is not identified as a separate 'element' of the safety case in Figure 2; rather its essential role in the safety case means that aspects of safety assessment relate to many elements of the safety case. The PAMINA safety assessment topics are introduced below and described in more detail in chapters 4-14 of this Handbook.

Safety Strategy – This is itself an essential element of the safety case. Work on safety strategy in PAMINA has largely focused on the safety assessment strategy, but recognises the additional important components of siting and design and management strategy.

Safety Functions – These are those properties of the engineered and natural barriers that provide safety. Specific safety functions will depend on the disposal concept, but generally include functions related to isolation, containment and retardation of the radiation associated with the wastes. These safety functions are an important part of the assessment basis.

Safety Indicators and Performance/Function Indicators – These are benchmarks used to demonstrate the safety and performance of the repository system. Discussion of safety indicators makes an essential contribution to the evidence, analyses and arguments of the safety case.

Analysis of the Evolution of the Repository System – An understanding of the repository system evolution is a key aspect of the assessment basis and underpins the safety analyses within the safety case.

Definition and Assessment of Scenarios – Scenarios form an important aspect of the assessment basis for a safety case. The evolution of the repository system is analysed under a set of scenarios, which may have varying likelihoods of occurring. The safety case is likely to consider scenarios that reflect the expected evolution of the repository system, as well as 'what if?' scenarios. The latter may be used to explore unlikely eventualities as well as to test the robustness of the safety case to the impairment or failure of safety functions (for example by exploring the impact of early failure of the waste containers).

Human Intrusion – This is one of the scenarios generally considered in a safety case. Human intrusion discusses the disturbance of the waste containers by human activity (for example drilling into the engineered barriers of the repository system). Many national regulations give clear guidance on the methods for treating human intrusion, for example prescribing the scenarios to be considered, or only requiring consideration of inadvertent intrusion, in which the intruders are unaware of the location or contents of the repository. Many safety cases also discuss ways in which the risk of human intrusion can be avoided, for example through increased depth of the repository and siting in an area with no minerals or other resources of economic value. Consideration of human intrusion therefore also forms part of the siting and design strategy within the safety case.

Biosphere – As the biosphere represents the environment generally accessible to humans, many of the safety criteria relate to the impact of radiation derived from the wastes in the biosphere. The biosphere is a dynamic environment with many transient processes operating, various stylised approaches have therefore been developed and agreed internationally for modelling the biosphere, for example the 'reference biospheres' developed by the BIOMASS project [IAEA, 2003]. National regulations may also specify the approach for dealing with the biosphere, as part of the assessment basis.

Modelling Strategy – The modelling strategy is a key aspect of the assessment strategy and the means for undertaking quantitative analyses of the repository system. Demonstrating and justifying a robust approach to modelling is a key element of building confidence in the safety case.

Criteria for Input and Data Selection – Models require data, and this PAMINA topic discusses the basis on which data are used in the safety analyses. All data form part of the assessment basis.

Uncertainty Management and Uncertainty Analysis – Management of uncertainty is at the heart of any long-term safety case. A clear strategy for managing uncertainty forms part of the overall safety strategy within a safety case. Analysis of the uncertainties should also be discussed alongside the safety analyses and arguments and included as part of the statement of confidence in the safety case synthesis.

Sensitivity Analysis – This is an important aspect of the safety analysis and is used to identify the impacts on the safety criteria of varying the values of uncertain model parameters.

2.3 References

[IAEA, 2003] "Reference Biospheres" for Solid Radioactive Waste Disposal, Report of BIOMASS Theme 1 of the BIOsphere Modelling and ASSessment (BIOMASS) Programme, IAEA BIOMASS-6, IAEA, Vienna, Austria, 2003.

[NEA, 2004] Post-closure Safety Case for Geological Repositories: Nature and Purpose, ISBN 92-64-02075-6, OECD-NEA, 2004.

[Nirex, 2005] Performance Assessment in Context, Nirex Report No. N/117, United Kingdom Nirex Ltd, March 2005.

3. National context

3.1 Belgium

3.1.1 Context of the implementer in Belgium (ONDRAF/NIRAS – SCK/CEN)

The Belgian research programme related to the safety and feasibility of the geological disposal of B&C wastes (high-level and long-lived wastes) has been launched in the 1970s by SCK/CEN. The studies have been focused on the Boom Clay in northeast Belgium as a potential host formation for a geological repository. The state of scientific and technical research on the possible final disposal carried out in the period 1990-2000 was presented by ONDRAF/NIRAS in the SAFIR 2 (Safety Assessment and Feasibility Interim Report 2) report in 2001.

The Belgian Federal Agency for Nuclear (FANC) has the obligation, conform to the law of 1994, to be informed on ongoing research and to encourage new research and development on this matter.

The next scientific and technological milestone of the B&C Programme led by ONDRAF/NIRAS in close collaboration with SCK/CEN is the development of a first “safety and feasibility case" (SFC 1) planned for 2013. SFC 1 will consider a reference disposal system constructed in a well-defined zone in the Boom Clay. Disposal in Boom Clay is currently regarded as the reference “working hypothesis”. Ypresian clay will be also considered as an alternative host formation in SFC 1 but with much less details. The objective of the SFC 1 is to substantiate that for all currently foreseeable B&C waste streams considered in the Belgian programme and within the defined zone, the proposed disposal system has the capacity to ensure passive long-term safety and operational safety, and that the proposed design is judged feasible. The elaboration of the SFC 1 is divided into three steps. The first step consists in the development of the scientific and technological knowledge (the assessment basis). It has been initiated in 2004 and takes place until 2011. The methodologies and modelling tools for safety assessment are developed in the same period. From 2011 a formal safety assessment will be conducted which will last one year. In the last stage a consolidation step is foreseen to structure and ensure the coherency of the substantiation elements of the SFC 1.

If the Belgian government confirms the working hypothesis of geological disposal in a clay formation and decides on the basis of the results of SFC 1 to launch the process that would eventually lead to the final choice of a disposal site, a second safety and feasibility case is foreseen. SFC 2 will ideally be site-specific and seek to provide evidence of the absence of any major safety- or feasibility-related obstacle to implementation. Based on the SFC 2, a go-ahead for launching the detailed studies on a specific site needed to prepare licensing applications could be given. This planning is not tightened to a strict timeline but the current R&D financing agreements locate the first licence application around 2025.

3.1.2 Regulatory Context in Belgium (FANC)

The Royal Decree of 20 July 2001 (laying down the general regulation on the protection of the population, the workers and the environment against the hazards of ionizing radiation) outlines the main regulatory provisions that operators of nuclear facilities and carriers of nuclear materials must comply with in order to ensure that nuclear energy and the applications involving ionizing radiation are used safely. This decree transposed, amongst others, the European Directive 96/29/Euratom into Belgian law.

According to this Royal Decree, radioactive waste disposal facilities are class 1 facilities and, therefore, the creation and operation licenses regime applies as set out in this Royal Decree.

However, the existing regulation doesn't cover the specific aspects related to a disposal facility, like the long-term aspects of the radioactive waste management and the stepwise approach required to manage the licensing process on very large timescales.

Consequently, it has been decided to develop a specific Royal Decree about long-term management of radioactive waste, applicable to both near-surface and geological disposal facilities. This new Decree is under development based on a strategic note where FANC has set out its policy regarding license applications for disposal facilities in Belgium. This strategic note has been issued in 2007. A phased process consisting of 5 successive authorisations to be issued throughout the lifetime of a repository is established: authorisation for construction and operation; starting for closure; closure; surveillance phase; release from regulatory nuclear control. The first license application includes the Safety Case comprising a Safety Assessment Report and an Environmental Impact Assessment Report. These documents have to cover both the operational and the post-closure periods, demonstrating operational and long-term safety. The Safety Case has to be regularly updated and in particular, the Safety Assessment Report has to be re-evaluated at least at the end of each phase and submitted to the nuclear safety authority with the application for entering the following phase.

In line with the development of the new aforementioned regulation for radioactive waste disposal, technical guidance texts are being developed, for near-surface disposal, as an application for such a facility is planned to be submitted within the next two years, but also for geological disposal, in order to get a comprehensive and coherent regulatory framework. Some of those documents will be common to all types of disposal facilities (e.g. guidances on safety strategy, safety case, biosphere, monitoring,...).

3.2 Czech Republic

Systematic survey of possible sites for a Deep Geological Repository (DGR) started in the Czech Republic already in 1988 and until 2002 six relatively suitable sites were selected for more detailed non/destructive geological research. All candidate sites are located in granite. At present, due to strong opposition of public in selected sites, geological works that need invasion to sites were interrupted until 2009.

The systematic accumulation and assessment of scientific and technical data for proposal of design, selection of EBS system and safety evaluation of DGR started in the Czech Republic in 1993 in a project coordinated by Nuclear Research Institute Rez (NRI) and funded by Ministry of Trade and Industry. The results from this period were in 1999 summarized in so-called “Reference design report” of the deep geological repository. The proposed reference design was similar to KBS 3 concept of disposal of spent fuel assemblies in granite in a vertical position. The repository layout in granite host rock consists in spent fuel waste packages surrounded by bentonite bricks and located in the tunnels at least 500 m under the surface. Instead of copper based canisters carbon steel canisters were proposed for assemblies from VVER reactors.

In 1997 the Act on the Peaceful Utilization of Nuclear Energy and Ionizing Radiation (the so-called Atomic Act) was approved by Parliament. This act (among others) established the Radioactive Waste Repository Authority (RAWRA), a state organization, which is responsible for preparation of a Deep Geological Repository (DGR), including coordination of R&D activities.

The Czech DGR development program is now divided into the following parts:

- Selection of suitable sites for DGR.
- Proposal of repository design, including selection and characterization of suitable engineered barrier system.
- Evaluation of safety of the disposal system and safety report preparation.
- Related technical research and development.

The first milestone for research and development activities will be in 2017, when two sites (candidate and reserve) should be selected for inclusion into land use plans.

Since 2017 to 2025 geological work should be performed on “candidate” site. On the basis of the geological work, design of the repository will be updated. Properties of engineered barriers will be studied taking into account the results from the site.

In the period 2025 – 2030 a confirmation underground laboratory should be prepared on site, in the case that the site is found acceptable. The construction and operation of the laboratory can be, however, postponed on the basis of results obtained from abroad laboratories.

In the period 2030 – 2065, underground laboratory and first modules of the repository shall be excavated. After 2050 also the construction of the surface premises shall start, including possibly an encapsulation plant. It is expected that the deep geological repository will be put into operation in 2065.

In 2008 RAWRA launched a new project with the aim to update reference design of DGR accommodating a new knowledge acquired since 1997 in Czech R&D projects and also abroad DGR development programmes. This project is coordinated by NRI and should finish in 2011 by a proposal of an updated conceptual reference design of DGR and a conceptual safety case. In addition to direct disposal of spent fuel assemblies in carbon steel canisters a disposal of spent fuel assemblies in copper based canisters and disposal of vitrified waste from spent fuel reprocessing will be considered.

3.3 Finland

Since the early 80's, a planning leading to the development of a geologic repository in Finland has been followed and these main milestones accomplished:

Status of the national programme:

1983-1985: Site identification surveys to select sites for preliminary investigations

1986-1992: Preliminary site investigations and safety assessment TVO-92

1993-2000: Detailed site investigations and safety assessment TILA-99

In 1999: Posiva proposed Olkiluoto in the municipality of Eurajoki as the site for the final disposal facility

In 2000: The Government made a policy decision in favour of the project in December 2000.

In 2001: The Parliament ratified the Government's policy decision in May 2001 by 159 votes to 3. After that the Municipal Council of Eurajoki approved siting the final disposal facility at Olkiluoto by 20 votes to 7.

2001-2003: Posiva focused further investigations on Olkiluoto and began preparations for the construction of an underground characterisation facility, ONKALO, which will form part of the final disposal facility.

In 2003: The municipality of Eurajoki granted a building permit for the ONKALO in August 2003.

In 2004: The construction of the ONKALO started in June 2004 and excavations of the access tunnel started at the end of September 2004. The construction of and installations in the ONKALO are to be carried out between 2004 and 2011 together with characterisation and investigations to support the application of construction licence due to 2012.

The major constraints that may modify the planning are:

- The Finnish authorities are responsible for establishing the principles governing nuclear waste management, safety criteria and for supervising the compliance with legislation. The Ministry of Trade and Industry (KTM) is responsible for the supreme command and control of nuclear matters. This includes granting licenses, formulating legislation and ascertaining that provision for the cost of nuclear waste management is arranged in the National Nuclear Waste Management Fund. The Radiation and Nuclear Safety Authority (STUK) is responsible for the control and supervision of nuclear and radiation safety.

- Specific requirements on the safety of the disposal of spent nuclear fuel are provided by the Government Decision 25 March 1999/478.

Licenses and other permits:

- Separate applications will be submitted to the Government later for licenses to construct and operate the final disposal facility. At present, the application for the construction license is scheduled for the early part of the next decade and the operating license for 2020. In addition to the long-term safety case, the operating license also requires an assessment by STUK as to the safety of the facility's operations.
- A building permit is required from the municipality of Eurajoki to build the infrastructure needed for final disposal. The required plans include a regional plan, a master plan and a local or detailed plan.
- All transport of radioactive materials requires a license from STUK. The licenses specified in compulsory purchase legislation and possibly also in the Electricity Market Act are required to construct power lines. The construction of public roads requires a ratification of a decision as specified in the Road Act.
- The final disposal of nuclear waste is also subject to the provisions of several international treaties and recommendations, including those of Euratom, the International Atomic Energy Agency (IAEA), and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive waste Management.

The current preparation of Posiva's Safety Case and the conclusion will affect two major decisions (i.e. the decisions will be based on the conclusions of the current safety case):

In 2012: The construction license application for the final disposal facility.

In 2018: The operation license application in order to take the final disposal facility into operation in 2020.

3.4 France

The December 30, 1991 French Waste Act [JORF, 1991] entrusted Andra, the French national agency for radioactive waste management, with the task of assessing the feasibility of deep geological disposal. The studies carried out within this framework were presented in the "Dossier 2005 Argile" (clay) [Andra, 2005a] and "Dossier 2005 Granite" [Andra, 2005b].

The Dossier 2005 Argile represents the period of 15 years since the law of 1991: a feasibility assessment stage. The feasibility study of a repository is intended to assess the conditions under which it would be possible to construct, operate, manage with a rationale of reversibility, close and monitor a repository and then let it evolve without any human intervention and without human safety and environmental protection being at stake at any moment.

The quality of the results produced within the framework of the Dossier 2005 Argile is based on an assessment system provided by the Waste Act of 1991 and ordered by Andra's trustee ministries or implemented by the initiative of the Agency itself. To that effect, the Act created an independent National Review Board to inform and advise the government on the interim progress at the technical and scientific levels. Since its inception and up to the production of the Dossier 2005, it has regularly listened to the Agency's scientists on all kinds of topics related to knowledge acquisition, modelling and engineering. In furtherance of the avenue of research related to deep geological disposal and Underground Research Laboratories (URLs), a siting phase initiated in 1993 through a consultation mission led by Mr Bataille identified four candidate sites (two of them were combined into one area). Beginning in 1994, Andra started preliminary geological and geophysical surveys and drilled exploratory boreholes in these three different areas of France. In 1996, three applications, backed by these preliminary studies, were filed by Andra to obtain construction and operating licences for underground laboratories so that in situ R&D programmes could be pursued. By the end of 1998, the French government took a twofold political decision concerning the Andra projects: 1) it authorised the construction and operation of an URL at the Eastern site, and 2) it did not authorise work at the other sites and started a new siting process with another consultation mission in order to find a new site with outcropping granite.

After the decree formalising the Eastern site decision (August 1999), Andra began its in situ R&D Programme for the Meuse and Haute-Marne area. The construction of the URL started in September 2000, after the authorisation to sink two shafts was granted by the government on 7 August 2000. To prepare for the 2006 comprehensive assessment by the French government and Parliament required by the Waste Act, Andra set out to produce an intermediate milestone report in 2001 for the Projet HAVL Argile, the Dossier 2001 Argile [Andra, 2001] leading up to the final Dossier 2005 Argile, which is a conclusive study and is an essential input to the future political decision-making process in France. At the request of Andra's trustee ministries, a peer review was organised between October 2002 and February 2003 to assess Andra's programme in the Dossier 2001 Argile with respect to international practices [NEA, 2003]. The review was organised by the Nuclear Energy Agency of the OECD; it included international experts from either Andra counterparts or safety authorities' research or technical support organisations.

Accompanying the publishing of the dossier 2005 Argile, three main steps occurred:

- From July to December 2005, reviews of the Dossier 2005 were conducted by the regulatory authority (ASN with the help of the technical support IRSN), by the National Evaluation Council (CNE) and by an international review team under the auspices of the NEA.
- September 2005 to January 2006; a national public debate was organised.
- On 28 June 2006, the new 2006 French Programme Act is published [XXX, 2006]. It was first adopted by the National Assembly on 12 April, and adopted by the Senate on 31 May, then second and final reading and adoption by the National Assembly on 15 June 2006.

According to the new French Act, reversible waste disposal in a deep geological formation and corresponding studies and investigations shall be conducted with a view to selecting a suitable site and to designing a repository in such a way that, on the basis of the conclusions of those studies, the application for the authorisation of such repository be reviewed in 2015 and, subject to that authorisation, that the repository be commissioned in 2025.

Andra follows an iterative approach for repository development (Figure 3), that allows modification and refinement of the choices regarding design and prioritisation of research on the basis of feedback from science and safety studies. The design solutions are optimised iteratively to maximise robustness with respect to key uncertainties in the safety case.

Three main iteration loops have been identified since 1991, each corresponding to a major milestone of the program: License application for construction and operation of the underground research laboratory (in 1996), submission of the Dossier 2001 (in December 2001), and the recent submission of the Dossier 2005.

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3.5 Germany

According to the Atomic Energy Act [ATG, 1985] the German Federal Government has to ensure the safe disposal of radioactive waste by providing repositories. The legal basis for licensing of federal installations for the safekeeping and final disposal of radioactive waste is the "Plan Approval Procedure" required by the Atomic Energy Act. Radioactive waste disposal policy in Germany is based on the decision that all types of radioactive waste are to be disposed of in deep geological formations. The currently valid safety criteria for the final disposal of radioactive waste in a mine dates from 1983 [BMI, 1983]. Since then, regulatory expectations have advanced, now reflecting the international standards set out by ICRP [ICRP, 1998], NEA [NEA, 2004] and IAEA [IAEA, 2006]. On this account, GRS proposed "Safety requirements for the disposal of high active wastes in deep geological formations" [Baltes, 2007] on behalf of BMU (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), which is expected to serve as a sound basis for a new regulation. The

BMU is presently elaborating the final version of the Safety Requirements. A draft version of the Safety Requirements was presented in November 2008 to the public [BMU, 2008].

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 radioactive waste. In the former German Democratic Republic short-lived low- and intermediate-level radioactive waste was disposed of in the Morsleben repository, a former rock salt and potash mine.

The **Konrad** repository had been licensed in May 2002. All suits that were filed against it were rejected by the competent court in 2006. Complaints against the courts decision were definitely rejected by the Federal Administrative Court in April 2007. Following necessary planning adjustments the former iron ore mine will be converted into a repository for all kinds of radioactive waste with negligible heat generation by the end of 2013.

The disused salt and potash mine Morsleben (ERAM), located in the Federal State of Saxony-Anhalt, has been in operation since 1971 as a repository for short-lived low- and intermediate-level radioactive waste. Disposal was terminated in 1998. A waste volume of about 37,000 m^3 has been disposed of with a total activity of approx. $4.5 \cdot 10^{14}$Bq. Since 1990, the Morsleben facility has the status of a federal repository. The license for operating the repository originates from the former German Democratic Republic and do not include the license for the closure of the repository. Therefore, according to the German Atomic Energy Act [ATG, 1985] a license application for the closure of the repository is being prepared by BfS (Federal Office for Radiation Protection).

The Gorleben salt dome in the north-east of Lower Saxony has been investigated for its suitability to host a repository for all types of solid and solidified radioactive waste for several decades. However, after the licensing of the Konrad repository the focus is mainly on heat generating radioactive waste originating from reprocessing and spent fuel elements. The exploration of the Gorleben salt dome was interrupted on 1st October 2000 according to a moratorium of up to 10 years.

The German radioactive waste management and disposal concept as well as the site selection process are still under discussion. In terms of the site selection process, a re-spective concept from BMU was suggested in 2006. This concept includes the examination whether site alternatives exist in addition to Gorleben, which let expect or possess a higher level of safety [Gabriel, 2008].

The current R&D concept focuses on all types of host rocks, prioritised in the following order: rock salt, argillaceous rock, crystalline rock. Concerning rock salt, which has been the preferred option in Germany for several decades, the technical and engineering know-how as well as the scientific expertise are considered well advanced and are now available for the conceptual design of a high level waste repository. During the last 10 to 15 years suitable analytical tools have been continuously developed according to the world wide advancing state-of-the-art. They are ready to be tested and applied at appropriate and concrete cases. For repositories in argillaceous and crystalline rock R&D work focussing mainly on mechanical and hydraulic properties of the engineered and the geological barriers has been performed during the last decade. System models for an integrated safety assessment are available for both formations.

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3.6 The Netherlands

A stepwise approach to finding waste management options that are feasible, suitable and acceptable, in both technological and societal respect, is a central policy consideration of the Dutch Government. Based on three policy documents, published respectively in 1984 [MoH, 1984], 1993 [DG, 1993] and 2002 [MoVROM, 2002], the current strategy in the Netherlands can be summarized as follows:

- long-term interim storage in a purpose-built facility at COVRA (Centrale Organisatie Voor Radioactief Afval) for at least 100 years,
- ongoing research, preferably in international collaborative programs,
- eventually retrievable deep geological disposal.

In the Netherlands, potential host formations are salt domes and plastic Boom clay. As result of the 1993 retrievability requirement, the then existing generic designs were modified to allow retrieval of the waste packages after emplacement and sealing of the disposal cells. The safety assessment shows that these designs meet the relevant criteria for operational and long-term safety.

The economy-of-scale of the nuclear power programs limits the options for the geological disposal of radioactive waste in the Netherlands. For countries with small nuclear power programs, such as the Netherlands, economies-of-scale will force them either to implement long-term storage and wait for decades, and/or to share a repository with others.

The research on radioactive waste disposal started in the early seventies. It was pointed out that rock salt formations in the Netherlands could serve as host rock for a disposal facility. In the late 1980's the VEOS study (Safety evaluation of disposal concepts in rock salt) has been performed in the Netherlands [Prij, 1990]. The aims of this study were the evaluation of the post-closure safety of some possible disposal concepts and the determination of relevant characteristics. VEOS used a scenario approach followed by a deterministic consequence analysis and several deterministic sensitivity studies.

In the early 1990's a generic probabilistic safety analysis (PROSA, [PROSA, 1993]) of the Dutch generic reference disposal concept has been performed. The PROSA study determined the radiological effects on humans and derived safety relevant characteristics of a disposal concept for radioactive waste. These characteristics have been derived from sensitivity analyses of the radiological consequences of some disposal concepts in rock salt formations. The PROSA study was restricted to the safety in the post-closure period.

The PROSA study was carried forward and extended in the CORA program [CORA, 2001], in which the options for retrievable storage and disposal of radioactive waste in the Netherlands were investigated, both for a salt-based and clay based repository. These two types of host rock are both abundantly present in the Netherlands. However, there are currently no actual plans to transfer this waste to a national deep geological repository.

The Dutch concept for an underground facility for disposal of radioactive waste is still being developed. In the Netherlands attention mainly has been focused on suitable salt domes in the northern part of the country and clay layers in the south. Since the Dutch radioactive waste will be stored in the COVRA (Central Organization for Radioactive Waste) surface interim storage facility for a long time (up to some 100 years) the decision on a suitable concept is at present not a critical issue.

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3.7 Spain

ENRESA (Empresa Nacional de Residuos Radiactivos S.A.) was set up in 1984 to be responsible for radioactive waste management and decommissioning of nuclear facilities in Spain. In 1985 Enresa started working on deep geological disposal of the spent fuel and HLW, adopting a stepwise approach to develop a safe repository concept and demonstrate its feasibility. Work was performed in four basic directions [MITC, 2006]:

- Site Selection Program, that allowed identifying several granitic, clay and salt formations in Spain that could serve as appropriate host formations for a repository. The site identification program was stopped in 1996, and no particular site has been proposed as candidate for a repository.
- Development of generic repository concepts in the three aforementioned host rocks.
- An extensive R&D program in collaboration with Spanish universities and research centres to improve the scientific understanding of the processes that control the long term stability and isolation capability of the different barriers in the disposal system.

- Development of safety assessment methodologies and tools, and application to generic repository concepts (in clay and granite) potentially located in synthetic sites created on the base of data generated within the Site Selection Program.

The parallel development of these four components intends to provide useful inputs to each other, and after several iterations should lead to a robust, feasible and safe disposal system.

Since 2004 the resources allocated to the Spanish deep geological disposal program have decreased significantly and in-house developments are very limited. The information generated up to that instant and the repository generic designs were properly documented, and since 2004 the focus is to maintain the safety assessment capabilities, updating the previous exercises on the basis of the advances in a reduced national R&D program and the participation in international projects. In general, the evolution of the safety assessment activities has been performed following the common view on this topic developed by international organisations (NEA, IAEA).

Enresa has remained actively involved in international R&D projects, such as PAMINA, FUNMIG, etc., and is represented in international committees dealing with conceptual developments on repository safety, such as NEA´s Integration Group for the Safety Case (IGSC).

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3.8 United Kingdom

3.8.1 Regulations and guidelines

The UK regulation that would apply to radioactive discharges from a closed repository is the Radioactive Substances Act 1993 (RSA93) [HMSO 93]. This legislation is quite general, and applies to a great variety of situations where there may be discharges of radioactivity to the environment. Relevant agencies have therefore published guidance, known as the ‘Guidance on Requirements for Authorisation’ (GRA) [EA, 1997], which outlines how an application for an RSA93 authorisation would be judged in the specific case of land based disposal of solid radioactive waste (a geological disposal facility). The GRA was revised in 2008 and split into two documents, one dealing with near-surface disposal and another dealing with deep geological disposal. Following a public consultation, the updated guidance was issued in February 2009 [EA, 2009].

3.8.2 Development

Radioactive wastes have been produced in the UK for more than 50 years. In 2001 the UK Government initiated the Managing Radioactive Waste Safely (MRWS) programme to develop a publicly acceptable long-term management strategy for intermediate-level waste (ILW), high-level waste (HLW) and other higher activity radioactive wastes. This followed more than two decades of unsuccessful attempts to develop a geological disposal facility for ILW, which culminated in the refusal in 1997 by the then Secretary of State for the Environment for permission to build an underground experimental facility near Sellafield, in West Cumbria. After the planning appeal the performance assessment, Nirex 97 [Nirex, 1997] was published as an orderly wrap-up of the site investigation.

As part of the MRWS programme, an independent advisory body, the Committee on Radioactive Waste Management (CoRWM), was established in 2003. CoRWM led research and public debate, to evaluate options. Issues such as the safety, environmental impact, viability, security, flexibility, and burden on future generations were all considered in a staged assessment of various long-term waste management options.

In July 2006, CoRWM concluded that, within the context of present knowledge, it had sufficient confidence in geological disposal as the best method for long-term management of radioactive wastes. The relevant regulators also stated that they could, in principle, accept a long-term safety case for a geological disposal facility. CoRWM also recognised that continued storage is the only available option until a geological disposal facility is available several decades from now, and recommended that all new stores should incorporate increased security against accidents and terrorism.

CoRWM recommended that the implementation of the geological disposal facility should be based on the willingness of local communities to participate (‘voluntarism’) and the concept of partnership with the implementing organisation.

In October 2006, the UK Government endorsed CoRWM’s recommendations and nominated NDA as the UK’s implementing organisation for geological disposal, and began to consider the most appropriate framework for implementation. A public consultation on this framework was carried out, and in June 2008 the UK Government published the Managing Radioactive Waste Safely White Paper on this framework [DEFRA, 2008]. This White Paper was the formal start of the process of implementing deep geological disposal in the UK.

The UK has considerable experience in planning for geological disposal, and since 1997 has concentrated on generic work with the intention of increasing readiness when a site comes forward. This generic work has included, for example, research and development, and demonstration safety cases and modelling.

The UK has more than 25 years of site-specific and generic experience studying geological disposal and undertaking safety assessments in the UK, as well as learning from and collaborating with other national waste management organisations.

The UK is now embarking on a programme to implement a national geological disposal facility. As part of this process the UK Government is currently seeking expressions of interest from communities that may be interested in participating in the site selection process. The NDA has prepared a generic Disposal System Safety Case (DSSC) as an input to initial site studies [NDA, 2010]. We envisage future developments of the DSSC to support the different stages in the development of the geological disposal facility.

3.8.3 Summary

A solution for the long-term management of higher activity wastes has been sought for over two decades in the UK. After due consideration the Government has decided geological disposal is the preferred option for disposal of these wastes. The process to implement geological disposal is now underway in the UK. The NDA has develoepd a generic safety case to provide evidence to demonstrate that a suitably sited geological disposal system could be designed to meet all applicable regulatory criteria and be safe.

3.8.4 References

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4. Safety strategy

4.1 Introduction

Geological disposal of long-lived radioactive waste is being widely investigated as a means of protecting people and the environment from the waste for as long as it remains hazardous. A geological disposal facility is considered safe if it meets the relevant safety standards that are internationally recommended and those specified by the national regulator. The strategy developed and implemented to achieve the required safety standards is called a “safety strategy”. The Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) defines safety strategy in more detail as follows [NEA, 2004]:

“The safety strategy is the high-level approach adopted for achieving safe disposal, and includes an overall management strategy, a siting and design strategy and an assessment strategy. All national programmes aim at management strategies that accord with good management and engineering principles and practice. This includes maintaining sufficient flexibility within a step-wise planning and implementation process to cope with unexpected site features or technical difficulties and uncertainties that may be encountered, as well as to take advantage of advances in scientific understanding and engineering techniques. The siting and design strategy is generally based on principles that favour robustness and minimise uncertainty including the use of the multi-barrier concept. The assessment strategy must ensure that safety assessments capture, describe and analyse uncertainties that are relevant to safety, and investigate their effects.”

The safety case or safety report will incorporate the safety strategy as one of the building blocks in developing confidence in the demonstration of safety. A safety case regarding the long-term impacts associated with the disposal of radioactive waste is defined by the NEA as follows [NEA, 2004]:

“A safety case is the synthesis of evidence, analyses and arguments that quantify and substantiate a claim that the repository will be safe after closure and beyond the time when active control of the facility can be relied on.”

This chapter collates the views elicited from European organisations participating in the PAMINA Project on their safety approach and assessment strategy. The key concepts considered include the safety principles, the approach to safety, safety assessment structure, and safety management including quality assurance (QA). Summarised descriptions of the relevant national context, disposal system planning, and safety strategy structure of the respective countries provided by the participating organizations have been presented in chapter 3.

4.2 Regulatory Requirements and Guidance

National regulatory frameworks for geological disposal are at different stages of development; most are based on safety guidance provided at the international level (e.g. [NEA, 2004], [IAEA, 2006] and [ICRP, 2000]). The more advanced national regulatory frameworks complement fundamental dose and risk limits with safety requirements that aim to reinforce the demonstration of safety by suitable arguments and analyses in the safety case.

The **Belgian** regulator (FANC) has recently issued guidance on the management of license applications, which contains safety principles that apply to any disposal facility for radioactive waste in Belgium [FANC, 2007]. FANC is currently developing more detailed guidance for near-surface disposal facilities that will be issued by the end of 2010. The development of more detailed regulatory guidance for geological disposal facilities for high-level waste is also planned, and will be based in large part on the guidance developed for near-surface disposal facilities.

In the **Czech Republic**, the State Office for Nuclear Safety (SÚJB/SONS) is responsible for the licensing of a geological disposal facility. Reasonable assurance must be provided in the safety report (safety case) that doses to members of the public in the long term will not exceed 0.25 mSv per year for a normal evolution scenario [SÚJB, 2002].

The **Finnish** regulatory requirements on the safe disposal of spent nuclear fuel follow the recommendations in the Council of State Decision (478/1999) of 25 March 1999. The Decision places conditions on the geological characteristics of the site, the disposal facility depth, the nature of the barriers, and the implementation and timing of disposal. Also, criteria on long-term radiological performance are placed on the disposal system, in terms of dose to humans and other biota and release rates of long-lived radionuclides from the geosphere into the biosphere [STUK, 2001].

In **France**, the regulatory framework is based on guidance published by the Nuclear Safety Authority (ASN), among which the revised Basic Safety Rule n°III.2.f [ASN, 2008]. This guidance document includes the major regulatory expectations with respect to the fundamental objectives of a repository in deep geological formation including the base of concept and design development linked with safety (functions, characteristics of the host rock, engineered barrier) and the demonstration of the long term safety, including the safety assessment.

In **Germany**, GRS-K recently revised the “Safety Criteria for the Disposal Radioactive Waste in a Mine”, on behalf of the national regulatory authority, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). This work led to the development of “Safety Requirements on the Disposal of High-Radioactive Waste in Deep Geological Formations” [Baltes, 2007]. The specific requirements in the latter document cover all phases of development of geological repositories up to closure and beyond. They provide for a phased development process in which the technical, economic, planning and social aspects of disposal facility development are optimised. The ultimate goal of this process is primarily to ensure the containment and isolation of wastes over the long periods required to demonstrate compliance with the fundamental safety objectives for the protection of humans and the environment.[1]

[1] Based on this GRS-K proposal, in July 2008 the BMU submitted “Safety Requirements Governing the Final Disposal of Heat Generating radioactive Waste – Draft”, which is under consideration by the advisory bodies of the BMU.

To this end, GRS-K proposes several qualitative and quantitative requirements on disposal system safety that must be met in a safety case. These requirements concern compliance aspects related to:

- Safety principles (comprehensiveness, transparency, comprehensibility, multiple lines of evidence, the use of a safety culture);
- The elements that should be described in the safety case (scientific and technical knowledge, arguments and analyses); and
- Safety assessment calculations and documentation procedures.

In the **Netherlands**, a safety report must demonstrate that individual risks and doses are below the regulatory limits. However, a license application must also include an Environmental Impact Statement (EIS), which addresses (amongst other things) the International Commission on Radiological Protection (ICRP) principles for radiation protection, i.e. (1) justification, (2) optimisation, and (3) compliance with dose limits. The EIS can use the safety report to show compliance with the ICRP principles.

In **Spain**, the Nuclear Safety Council (CSN) has established a regulatory safety criterion for the disposal of radioactive waste in terms of a maximum allowable individual risk of 10^{-6} yr^{-1}. There are no specific regulatory requirements or guidelines regarding the strategy to be followed by the developer to demonstrate the safety of a geological disposal facility for HLW.

The **UK** regulatory framework is defined by the Radioactive Substances Act 1993 and the “Guidance on Requirements for Authorisation” (GRA), which outlines the safety principles and requirements that a developer of a disposal facility must meet. An updated GRA published in February 2009 [EA, 2009] contains a set of safety principles and more detailed requirements which, if met, are designed to ensure compliance with the safety principles; the principles and requirements concern protection of humans and the environment, and technical and management issues. The GRA differentiates between the requirements for near-surface disposal facilities and geological disposal facilities and introduces a staged authorisation process.

4.3 Key Terms and Concepts

The key terms and concepts related to safety approach and assessment strategy used further in this document are defined by international organisations such as the NEA, the International Atomic Energy Agency (IAEA) and the ICRP (e.g. [NEA, 2004], [IAEA, 2006], [ICRP, 2000] and [IAEA, 2003]):

Multiple safety functions: The natural and engineered barriers shall be selected and designed so as to ensure that post-closure safety is provided by means of multiple safety functions. That is, safety shall be provided by means of multiple barriers whose performance is achieved by diverse physical and chemical processes. The overall performance of the geological disposal system shall not be unduly dependent on a single barrier or function [IAEA, 2006]. The defence-in-depth concept relating to multiple barriers and multiple safety functions is discussed further in Section 4.4.1.

Robust systems are characterised by a lack of complex, poorly understood or difficult to characterise features or phenomena, ease of quality control, and the absence of, or relative insensitivity to detrimental phenomena arising either internally within the disposal system, or externally in the form of geological and climatic phenomena, and uncertainties with the potential to compromise safety [NEA, 2004].

Demonstrability forms a key concept in the development of a safety case. At the simplest level, the safety of a disposal facility is said to be demonstrated if all the safety requirements are met. However, as explained in Section 4.4.1, the concept of demonstrability is more subtle than this simple definition would suggest.

The **assessment basis** is formed by the information and the analysis tools available for safety assessment, and includes:

- The system concept, that is, a description of the disposal facility design including the engineered barriers, the geological setting and its stability, how the engineered and natural barriers are expected to evolve over time, and how they are expected to provide safety.
- The scientific and technical information and understanding, including the detailed support for the expected evolution of the disposal system and assessments of the uncertainties in scientific understanding.
- The methods of analysis, computer codes, models and databases that support the numerical modelling of the disposal system, its evolution and the quantification of its performance [IAEA, 2006].

Transparency: A safety case should be presented in ways that are understandable to the intended audiences; the objective is to inform the audiences' organisational or personal decisions regarding safety [IAEA, 2006].

Traceability: It must be possible to trace all key assumptions, data and their basis through the main safety case documents and supporting records [IAEA, 2006].

Model validation: In radioactive waste management, the process of building confidence that a model adequately represents a real system for a specific purpose [IAEA, 2003].

Model verification: The process of determining whether a computational model correctly implements the intended conceptual model and/or mathematical model [IAEA, 2003].

4.4 Treatment in the Safety Case

4.4.1 Safety principles and objectives

Geological disposal achieves the fundamental safety principles of containment and isolation of radioactive waste from the biosphere, without the need of future waste retrieval (although some disposal concepts provide for ease of retrievability for a limited period). These overall principles ensure the safety of humans and the environment without active measures or a need for long-term monitoring after sealing and closure of the disposal facility ("passive safety") [IAEA, 2006]. The safety objective that long-term radiological exposures should be as low as reasonably achievable (ALARA) is often specified to meet these overarching principles [e.g. Andra, NRG, NDA].

Although safety strategies vary amongst national programmes, some fundamental safety principles are shared by all organisations and serve to guide the development of the disposal facility design. In particular, the safety principles of multi-barriers/-functions, robustness and demonstrability form the founding principles of any coherent and pragmatic safety strategy.

IRSN, FANC/Bel V and GRS-K refer to the defence-in-depth concept used for designing nuclear power plants in defining the multi-barrier/-function principle for geological disposal facilities. The definitions used by most of these organisations are in line with the IAEA definition of multiple safety functions [IAEA, 2006]. FANC/Bel V consider that *"it is not the number and redundancy of the barriers as such that take on the greatest importance in terms of safety, but the fact of being able to depend on different mechanisms and/or components to provide safety functions."*

Posiva's safety strategy is based on the defence-in-depth concept, although Posiva considers that the long-term isolation and containment of radionuclides in copper/iron canisters is the most important factor for safety. The multi-barrier system, including the waste form, the buffer or backfill and the geosphere, helps to enhance the robustness of the overall system by providing redundant barriers [Posiva, 2008].

Demonstrability is seen as a major principle guiding safety strategy development - along with the robustness and defence-in-depth principles [e.g. Andra, IRSN, FANC/Bel V, ONDRAF/NIRAS-SCK/CEN]. However, absolute demonstration of safe geological disposal is not possible owing to the long period over which the disposal facility must be safe. Therefore, the safety of a disposal facility is said to be demonstrated if the design is shown to be simple, technically feasible and robust, that is, the functions of the disposal system will be fulfilled and maintained, no matter what reasonably foreseeable disturbances may impact the system. FANC/Bel V consider that the robustness of the disposal system can be demonstrated on the basis of the conservative assumptions used in performance assessment calculations, and the performance margins identified for the main components of the system.

Providing evidence that radiological safety standards and requirements are met is only one way of demonstrating safety. Considering demonstrability at a further strategic level, a safety case is said to be demonstrated if it also contains multiple lines of argument and analyses for safety justifications of the disposal system [e.g. Andra, GRS-K].

IRSN states that an important aspect to progress in safety demonstration (confidence building) is to provide a justified programme of investigation and studies to be carried out, consistent with the proposed sets of safety functions and components chosen in a particular stage of disposal system development. The programme must define the main safety demonstration issues during each stage of disposal system development, and the means to be implemented for safety assessment purposes. This includes monitoring of the disposal facility to ensure it is behaving as expected and according to the functions and characteristics assigned to the “controllable parameters” that are monitored during the different phases of disposal facility development.

Siting principles typically seek to minimise as much as possible the likelihood of inadvertent human intrusion, while maximising the geological stability of the host rock and the physical and chemical features favouring containment of radioactive waste. These principles typically state that siting should not compromise the future use of natural resources, and should focus on areas of relatively low population density [e.g. Posiva, Enresa, FANC/Bel V]. Technical factors guiding the selection of a suitable site typically include the thermal, hydrological, mechanical, and chemical (THMC) characteristics of the host rock, and its depth, thickness, and stability [e.g. Andra, Enresa, FANC/Bel V].

Only a few European organisations have reached the stage of detailed feasibility studies for particular sites. However, most organisations have undertaken generic feasibility studies. For example, the CORA study in the Netherlands demonstrated the feasibility, in principle, of geological disposal in salt and clay layers [CORA, 2001]. In contrast, Andra conducted a site-specific feasibility study in Dossier 2005 in order to assess the conditions under which it would be possible to construct, operate, manage with a rationale of reversibility, close, and monitor a geological disposal facility based on information from a selected clay formation (Callovo-Oxfordien) in Meuse-Haute-Marne where an underground research laboratory has been built. The notion of “feasibility” was driven by specific principles such as:

- There are technologies available that allow all phases of development of the disposal facility to be carried out safely.
- These technologies are easy to implement - in particular, the implementation does not necessitate any prohibitive development needs or costs.
- These technologies allow the disposal facility to be completed and kept open or closed under safe conditions.
- The short-term and long-term safety of the disposal facility can be assessed with sufficient confidence.

Although some organisations have developed facility designs to allow for reversible disposal in accordance with the principle of retrievability [e.g. Andra, NRG, Posiva], a final decision on whether or not to maintain this option will be taken in the future. In the case of Andra, the 2006 French act stipulates that studies are to be conducted for a reversible waste disposal in a deep geological formation in view of a site selection and authorisation of creation in 2015 and repository be commissioned in 2025. The tension between the objectives of not placing undue burdens on future generations and not impairing their right to make their own decisions may surface again as a point for debate once the closure stage of a disposal facility is reached.

4.4.2 Safety approach

4.4.2.1 The iterative approach to system and safety case development

All organisations agree on the necessity of integrating safety principles in an iterative and structured approach to guide disposal system development and to construct a sound (“demonstrable”) safety case. Through this iterative approach, the project groups responsible for knowledge acquisition, design, and safety assessment can interact efficiently and develop progressively a disposal facility consistent with the safety requirements.

As illustrated by Andra (Figure 3), this iterative approach allows modification and refinement of the choices regarding design and prioritisation of research on the basis of feedback from science and safety studies. The design solutions are optimised iteratively to maximise robustness with respect to key uncertainties in the safety case.

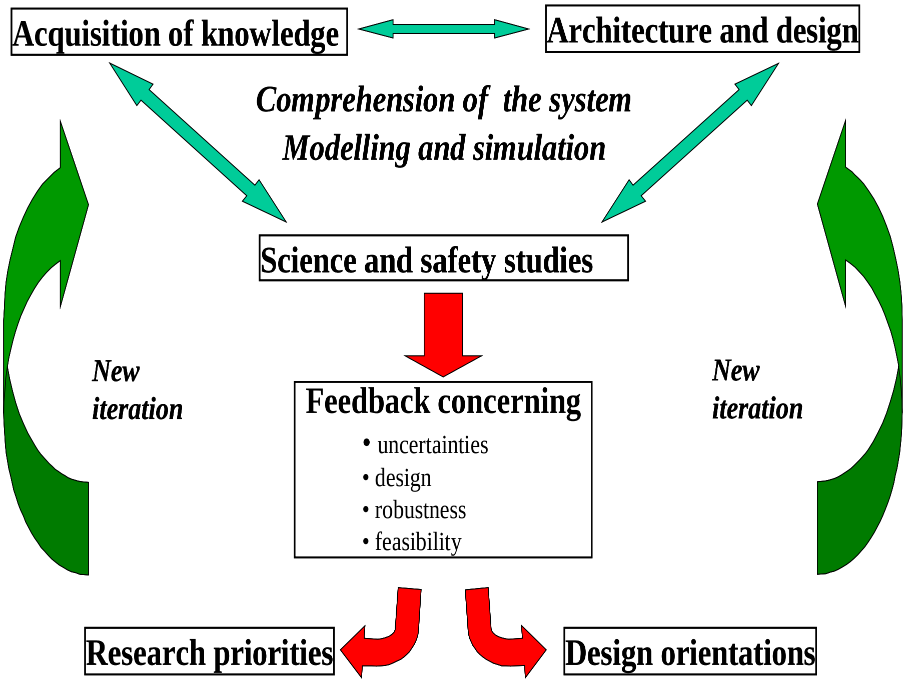

Figure 3 – Andra´s iterative approach to research and assessment [Andra, 2007].

The safety evaluators participating in RTDC 1 [GRS-K, FANC/Bel V, IRSN] consider that the iterative approach will be embodied in successive safety cases prepared at each major stage of the disposal facility development programme, incrementally building lines of argument and confidence in the safety of the disposal system.

GRS-K defines in its requirement for proof of safety that "The implementer has to develop the repository in a stepwise approach with an optimisation process to improve safety. In the stepwise approach, at each milestone the implementer has to prepare a safety case for safety demonstration. The safety case has to be comprehensive, transparent and comprehensible. The safety case can be adduced by bringing together all the arguments and analyses to justify the safety of the repository system and confidence in the safety statement."

IRSN has identified four elements that should be included in the safety case:

- The description of the safety strategy guiding any particular step of development of the project, through the definition of the safety functions assigned to the various components of the disposal system, and through the definition of the programme of investigation needed to confirm that these functions are effective.
- The implementation of the safety strategy providing a detailed description of the data, experiments and models acquired and developed during any particular step of the project development.
- A description of the safety assessments performed, aiming at verifying the soundness of the strategy proposed and that protection objectives are fulfilled.
- A synthesis of the results aimed at giving a statement of confidence in the safety demonstration of the disposal facility. This statement should describe how the multi-barrier/multi-function concept is effective and robust, and the technical feasibility of the disposal facility. The synthesis should discuss the remaining uncertainties and address whether these can be reduced by further research and how the safety strategy should be refined. Alternative design options should be kept under review in case a significant modification of the strategy becomes necessary.

This stepwise and iterative approach to the development of a safe disposal facility is fully endorsed by all the developers participating in RTDC 1. For example, Enresa states that a safety case assembling all relevant knowledge will be prepared for each important decision point in the programme. The safety case will be used to support the decision to be taken, and to identify any weak points in the safety assessment, prioritise research needs, and propose design modifications. Building on the findings of the safety case and other inputs (e.g., guidance from international organisations, feedback from the regulators, scientific developments), the disposal facility design, the safety assessment methodology, and the scientific knowledge base will improve between decision points. After several iterations, Enresa expects to have developed an optimised disposal facility design and a safety case that can be accepted by the regulator as demonstrating compliance with applicable standards and requirements.

4.4.2.2 Safety functions and the safety concept

The concept of multiple safety functions is a primary contributor to the development and implementation of the safety strategy for most organisations. For example, in the French programme, the safety functions - attributed to the components of the system via a functional analysis - guide the iterative approach. This functional analysis defines the technical specification in terms of requirements for the design and is a basic input data to the research and assessment program.

Posiva, ONDRAF/NIRAS SCK/CEN, and GRS-K refer to the “safety concept” to structure their safety strategies (Figure 4). Generally speaking, the safety concept explains how the disposal system provides long-term safety by integrating the multi-barrier/multi-function systems. The safety concept can also integrate high-level siting and design principles such as robustness and optimisation, as well as more detailed features of the disposal system (e.g. depth), management processes such as monitoring or QA, and disposal facility operational procedures that may influence long-term safety. The safety concept is used as a tool to guide the iterative safety approach, for example by helping to identify research priorities and to communicate the approach.

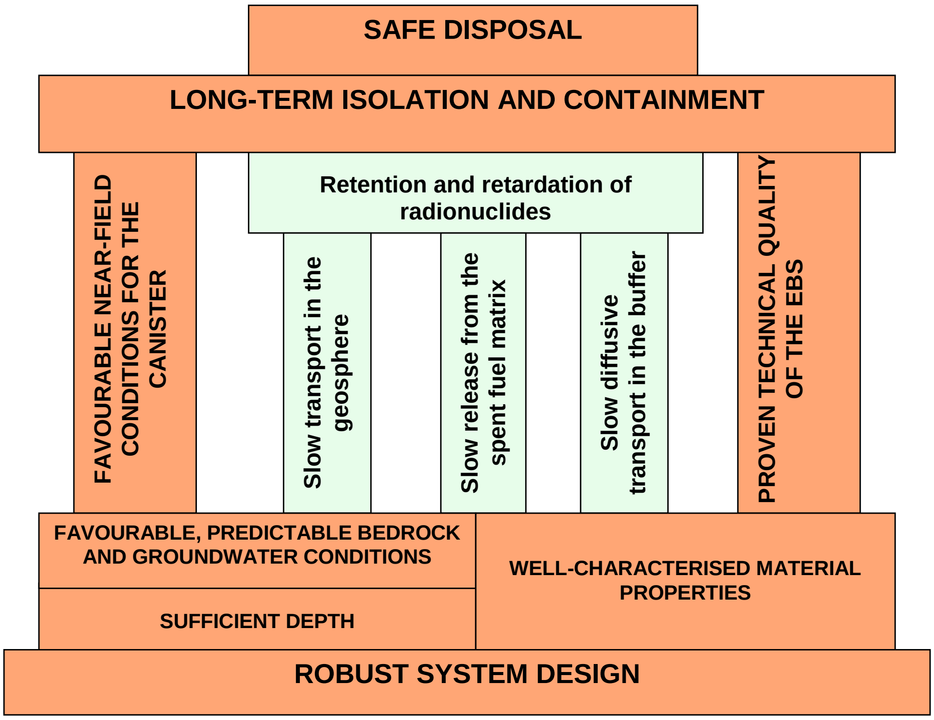

Figure 4 – Posiva´s safety concept for KBS-3 type disposal system for spent fuel in crystalline bedrock [Posiva, 2008].

For GRS-K, safety arguments and analyses should aim at evaluating and further justifying the safety concept and its realisation in the disposal facility design. The requirements to demonstrate safety and comply with the safety principles and protection objectives cover characterisation of the site and the engineered barrier system, and analysis of the system with respect to its ability to provide isolation and containment in the long term (e.g. consideration of system understanding and behaviour; scenario, model and parameter uncertainties; performance indicators; criticality safety).

ONDRAF/NIRAS SCK/CEN have translated the safety concept into a hierarchical set of safety and feasibility (S&F) statements (Figure 5). Each statement is an assertion about how components of the disposal system, specific management procedures or safety analysis results ensure an aspect of long-term safety in terms of safety functions, QA procedures or doses. This hierarchical set of S&F statements is constructed in a top-down manner, starting with the requirements that apply to the system as a whole, and progressing to more specific requirements on subsystems and components. Extending the idea of the safety concept, this set of S&F statements allows the identification of detailed R&D needs to reduce uncertainties and to provide traceable links between knowledge acquisition, safety assessment and design studies.

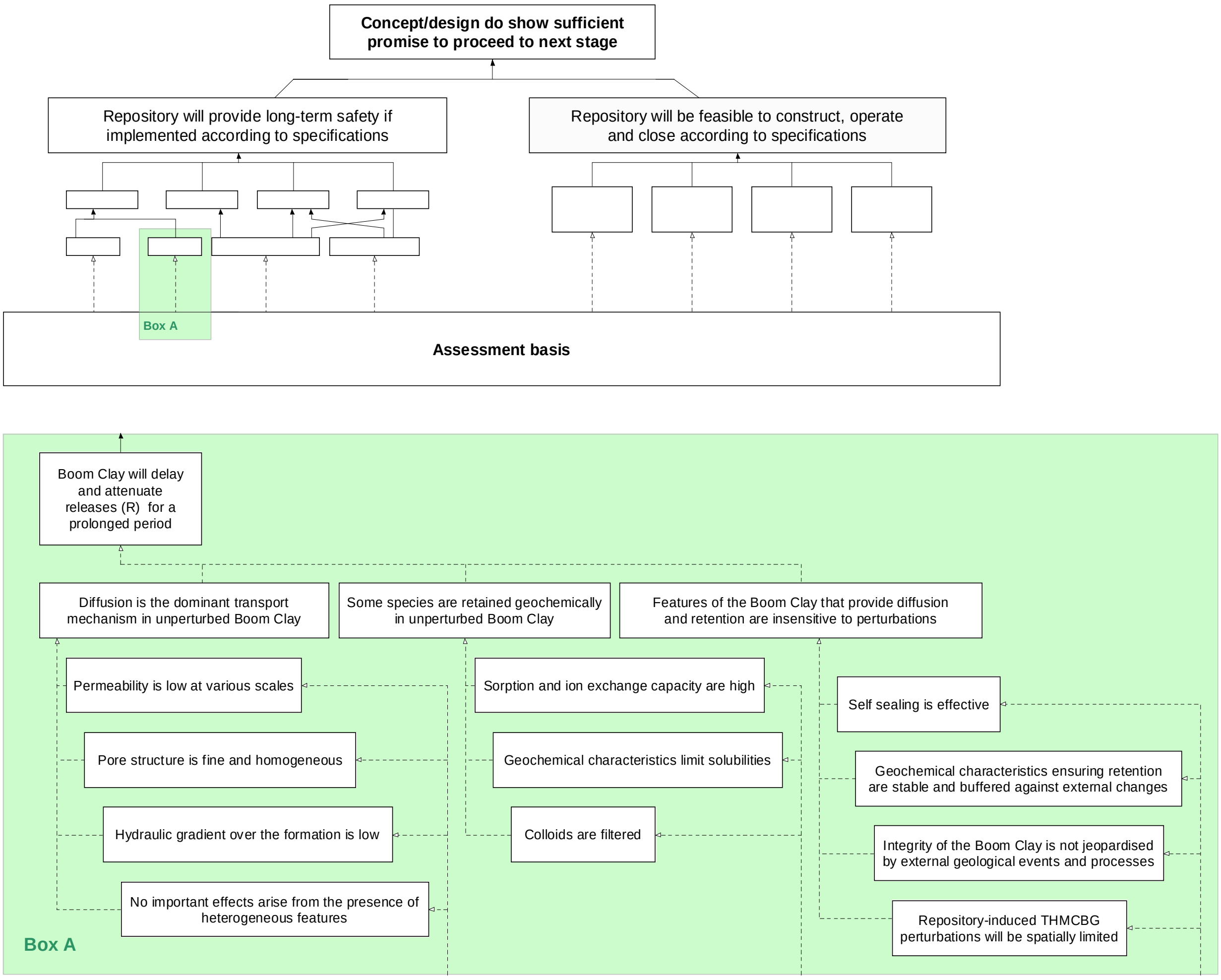

Figure 5 – Illustration of the first few levels of tentative structured set of safety and feasibility statements, expressed in terms of hypothesis [ONDRAF/NIRAS SCK/CEN]. The example shows safety statements related to safety functions.

4.4.3 Assessment basis and analysis

Most organisations refer to the definition given by the IAEA in [IAEA, 2006] for the assessment basis – see section 4.3. The term “analysis” in the section title is mostly seen as the “safety assessment” [e.g. ONDRAF/NIRAS SCK/CEN, IRSN, Enresa], which is underpinned by the assessment basis. A key part of a safety assessment is an uncertainty analysis to determine the impacts of uncertainties identified in the assessment basis on the long-term safety of the disposal system.

Generally, the methodologies adopted to perform the safety assessment of a geological disposal facility are similar to those described in the IAEA project “Improvement of Safety Assessment Methodologies for near-surface waste disposal facilities” (ISAM, Figure 6) [IAEA, 2004]. However, missing in Figure 6, but discussed by most contributors to this study, is the process of iterative feed-back between safety assessment and research and design studies (see below).

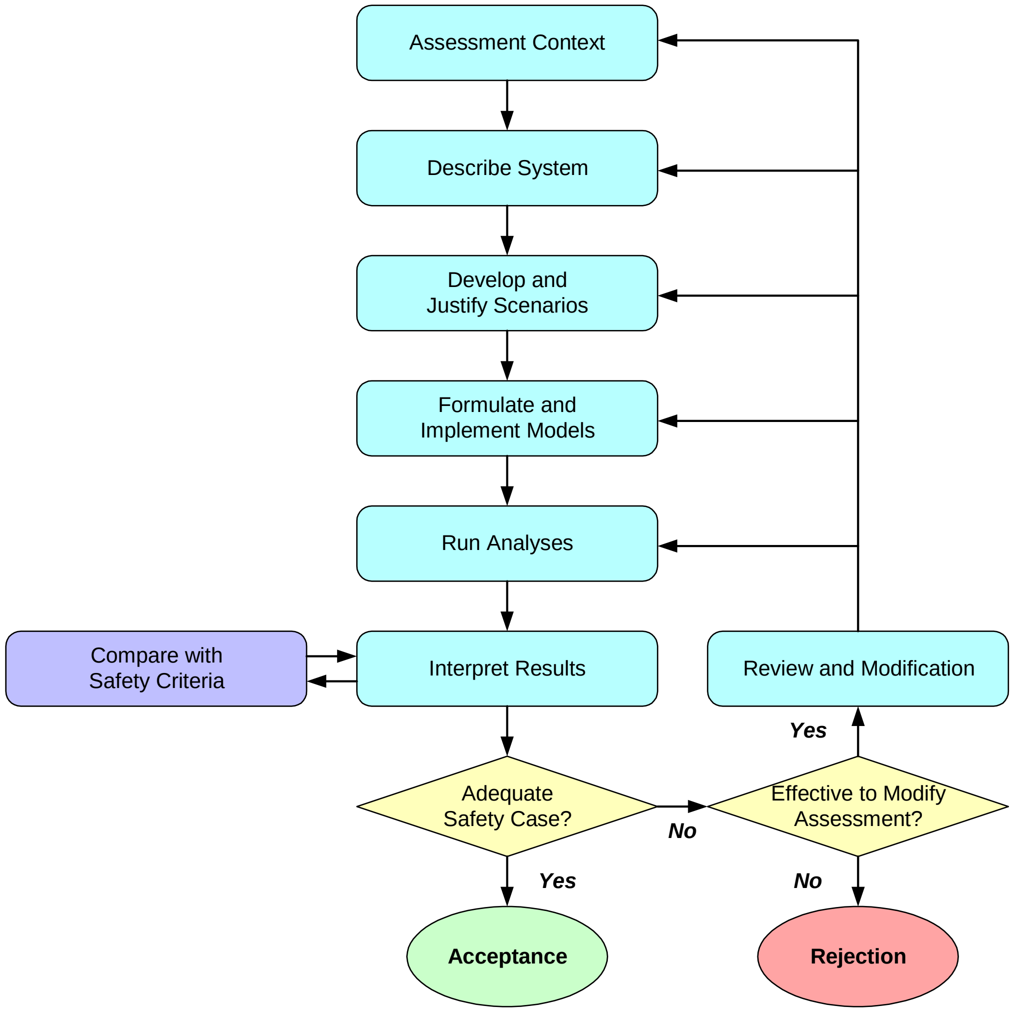

Figure 6 – The ISAM safety assessment methodology [IAEA, 2004].

Information regarding the purpose of the assessment, the regulatory requirements, the assessment end-points, and philosophy is provided as part of the assessment context. The safety functions and safety principles are also part of this starting point. The disposal system is then described from a phenomenological point of view and constitutes a key component of the assessment basis. A common trend in describing the system is to classify processes as to whether they are thermal, hydraulic, mechanical, chemical or relevant to radionuclide transport for a certain time frame of interest. The structuring elements are referred to variously as features, events and processes (FEPs), "situations" [Andra], or "dashboards" [ONDRAF/NIRAS SCK/CEN]. Where FEPs are used to structure the description of assessment basis, these are often screened and grouped into scenarios that represent different possible evolutions of the disposal system [e.g. Enresa, NRI/RAWRA, NDA, NRG, Posiva].

The next paragraphs summarise the relationship between assessment strategy and safety assessment for the French [Andra], Finnish [Posiva], and Belgian [ONDRAF/NIRAS SCK/CEN] assessment approaches.

In Andra's approach (Figure 7), the disposal facility architecture ("concept") is determined through the functional analysis (AF), which defines the safety functions that should be fullfilled by the main components of the disposal system.

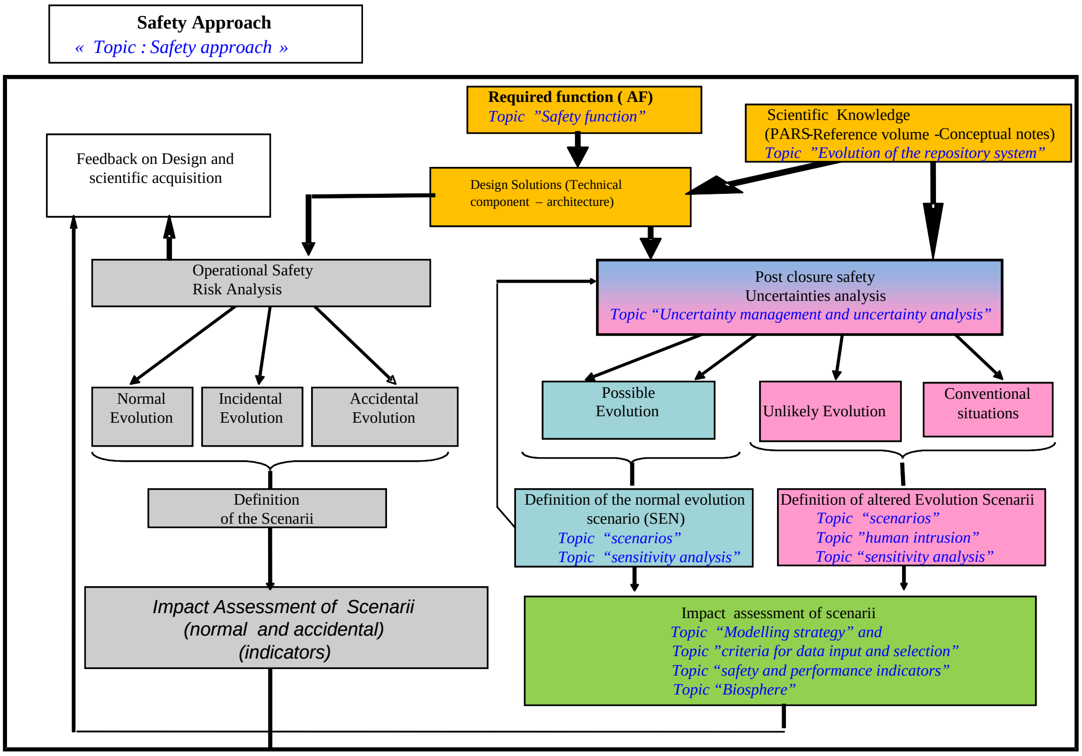

Figure 7 – Elements of the safety assessment performed by Andra [Andra, 2007].

This analysis defines the technical specifications in terms of requirements on each engineered component of the disposal facility. Once the disposal facility architecture is defined, a phenomenological analysis of its possible evolutions (PARS) is performed, resulting in the determination of "situations" and their coupling in specific scenarios. A detailed uncertainty analysis ensures uncertainty management through design choices, and/or integration into scenarios (normal evolution scenario or altered evolution scenarios depending on their likelihood) including sensitivity cases. From results of scenario treatments, potential feedback to design and scientific acquisition can be established.

This general safety assessment approach is also followed by Posiva, where the requirements for the system are primarily defined on the basis of the safety concept. Following an iterative loop, system understanding is developed for which the uncertainties are identified, leading to identification of the priorities for the research and technical development programme and design activities, and to the definition and description of scenarios and assessment calculations (Figure 8).

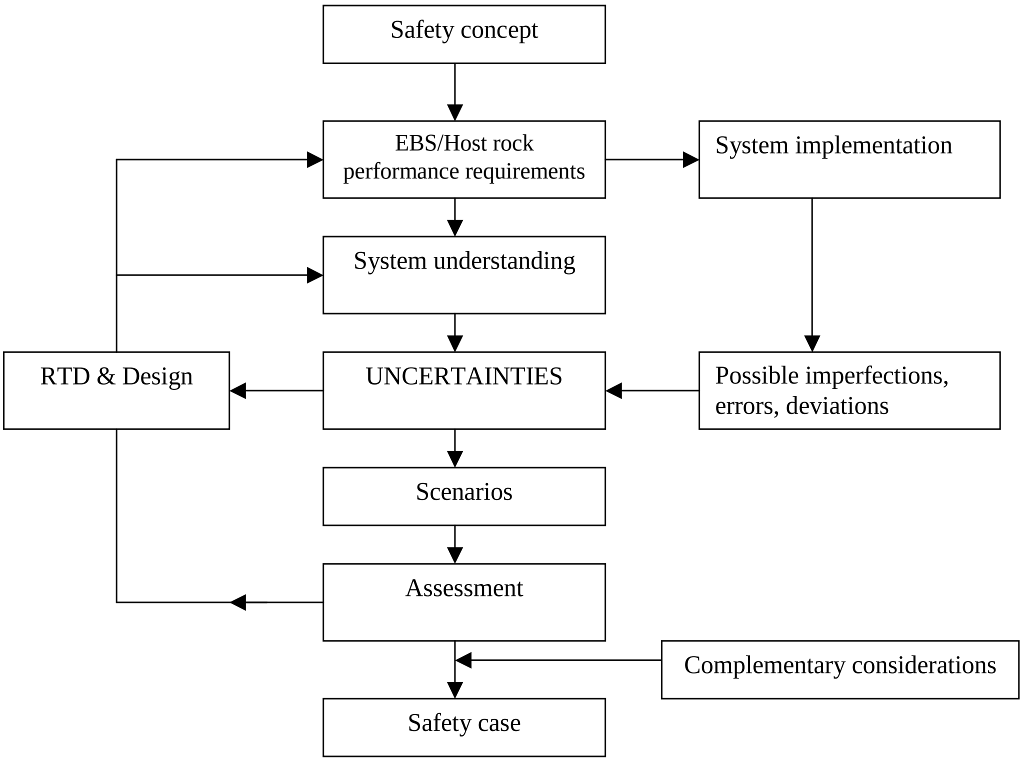

Figure 8 – Relationship among uncertainities, safety case and research and technical development (RTD) and design activities in the Posiva safety case [Posiva, 2008].

In the ONDRAF/NIRAS SCK/CEN programme, safety statements are used to structure the safety assessment and the associated uncertainty analysis. Safety assessment evaluates whether or not the disposal system provides passive long-term safety, if implemented according to design specifications. In order to meet this overall aim, uncertainties associated with the underlying assessment basis are evaluated. The propagation of these uncertainties through the safety statement set, and their potential impacts on the safety functions, are quantified. The calculated safety indicators are compared with regulatory targets in the form of safety statements.

4.4.4 Quality measures and organisational aspects

Project management plays an important role in the development of a safety case. It comprises among others, issues like teamwork, establishment and communication of project timeline, general QA, the specific issue of model QA, evaluation of “completeness”, and peer review.

Teamwork

All organisations agree on the necessity of an iterative process between the different project groups (e.g. assessment, design, research) in order to reduce assessment uncertainties and to optimise disposal facility design. These iterations require the integration of project groups in a coherent structure in which the role of each group is clearly specified.

Transparent and traceable communication between project groups is required, so that each cross-cutting issue can be treated jointly by the relevant experts. As the iterative interactions between the different groups of experts can vary in intensity and frequency as the programme evolves, there may be a need to adapt the organisational structure at key stages of the programme.

In order to reinforce the integration of the project groups, Posiva and Andra have created specific coordination units that collate and synthesise all information relevant to the activities in the safety case. Such units have responsibility for overall project management (e.g. feed-back and follow-up of research studies) to ensure the coherency of the project work within the overall safety strategy and safety assessment methodology, with particular attention to their inter-dependency.

Project timeline

Enresa, NDA and IRSN refer to the necessity of preparing a detailed roadmap, identifying clear milestones and decision points in the development of a disposal facility. In particular, Enresa and NDA note the benefit of early discussion with the relevant stakeholders, particularly the regulator, to define a project timeline and a common understanding of the main topics.

Andra integrates into its development plan, the major timelines according to the French Acts (1991 and the following one in 2006), and key milestones according to discussions with the French Safety Authorities (ASN).

QA procedures

Confidence in a safety assessment - and more generally in a safety case - does not solely rest on the intrinsic quality of the data and models used. It is also of prime importance to ensure that all data and models are obtained using systematic and well-defined procedures. These procedures are intended to provide, as much as possible, traceability, transparency, correctness and completeness. A first set of quality measures mentioned by many organisations concerns traceability and transparency of work flow within the organisations [Posiva, Andra, NDA]; implementation of the relevant quality procedures is typically subject to ISO 9001 certification.

The second series of quality measures concerns documentation. Developers and regulators indicate the necessity of having a QA system for project documents in order to keep track of the extensive information base that will be developed over many decades. Enresa identifies the need to define a hierarchical structure for the documentation, in order to deal with the large amount of detailed technical information generated over the long timescale of a disposal facility development programme. The safety case produced at different decision points would be based on this document hierarchy.

Model quality

Management tools are necessary to ensure the quality of the models used in a safety assessment. Three processes are identified that ensure that the models used are fit for purpose:

- At the first level, it is important to ensure that the conceptual models are broadly consistent with existing scientific understanding within the context in which the models are used [e.g. Posiva, ONDRAF/NIRAS SCK/CEN, NRG]. The simplifications of reality inherent in the development of a conceptual model have to be evaluated to ensure they are conservative. Evaluation of the impact of alternative conceptual models for representing a particular process can be a good way of checking the adequacy of current scientific understanding [e.g. Posiva].
- At a second level, the implementation of the conceptual model in a computational model has to be verified. Code verification can be demonstrated via benchmarking, error checking of the code, and comparison with simplified analytical solutions. Widely available and proven numerical modelling tools are often preferred over in-house code in order to reinforce confidence in the correctness of the modelling.
- The third-level check is the validation of the results of a computational model with independent *in situ* or laboratory observations. Validation is seldom possible in an absolute sense in the context of performance assessment models for radioactive waste disposal, owing to the long timescales involved in these assessments. It is for this reason that the IAEA defines validation as the process of building confidence that a model adequately represents a real system for a specific purpose ([IAEA, 2003], see Section 4.3).

Completeness

It is not possible to demonstrate with absolute certainty that the information base on which a safety assessment relies – that is, the assessment context – is complete. However, confidence in completeness can be promoted by expert reviewing and auditing of all elements of the safety case [Posiva]. A completeness check of the knowledge informing the assessment basis is performed by the majority of organisations, although it is not referred to formally as a quality procedure. In the ONDRAF/NIRAS programme, a FEP completeness check is performed on the assessment basis and on the scenarios derived in the safety assessment process.

Peer review

Some organisations have developed their current safety strategies and safety cases on the basis of earlier safety assessments that have been internationally peer reviewed. Such peer reviews can provide essential checks on the viability of a safety case. For example, in Belgium, following the international review of SAFIR 2 [NEA, 2003], the focus has been placed on the development of a “safety and feasibility case” based on safety and feasibility statements supported by a hierarchical collection of scientific and technical documents.

4.5 Conclusions

The safety strategy, as embodied in the safety approach and assessment strategy, is a key component of a safety case. The safety strategy defines the means by which safety is assured for a particular site and disposal concept. The safety strategy considers disposal facility design, assessment, and management functions:

- The safety strategy with respect to disposal facility design relies on a robust system of multiple safety functions, often with redundancy between functions or barriers.
- The safety strategy with respect to assessment relies on the use of international best practice, including such things as consideration of completeness, confidence in models and data, consideration of uncertainties, transparency and traceability.
- The safety strategy with respect to management relies on the establishment of focused and interacting teams, centred on delivering the design and assessment strategies, and an appropriate level of QA and peer review of activities.

All contributing organisations see the need for a stepwise development process that ensures a continuous building of confidence in the safety case. The early establishment of a comprehensive and fully integrated management structure is widely considered necessary to ensure effective development of a facility. A developer should establish early on appropriate QA and document control procedures and communication channels with stakeholders, particularly regulators. Some organisations [IRSN and GRS-K] suggest that consideration should be given to the provision of information in a safety case to address public concerns, such as the capability of a facility to be used for disposal of radioactive wastes arising from further development of the nuclear industry.

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5. Safety functions

5.1 Introduction

The concept of safety functions was already in use in 1980 for safety studies of nuclear power plants, e.g. [Corcoran, 1981]. During the development of the defence-in-depth concept [IAEA, 1996] for nuclear power plants, the multi-barriers concept was complemented with an approach ensuring the fulfilment of three basic safety functions: controlling the power, cooling the fuel and confining radioactive material.

Around 1995 the possibilities to apply the defence-in-depth concept to radioactive waste disposal were examined within the Swedish radioactive waste management programme. The starting point for the development of safety functions related to a geological repository was the main objective of radioactive waste management, i.e., to protect man and the environment from exposure to ionising radiation from radionuclides, which are present in the waste, now and in the future. The strategy adopted to achieve this objective is to concentrate and contain the waste and to isolate it from the biosphere [IAEA, 2006]. It was felt necessary to complement the multi-barriers principle with a set of safety functions that are provided by diverse mechanisms and components. Early applications of the concept of safety functions in safety evaluations of radioactive waste disposal can be found in the Swedish [SKB, 1999] Belgian [De Preter, 1999] and French [Andra, 2001] radioactive waste management programmes.

5.2 Regulations and guidelines

As the concept of safety functions is relatively new in the context of safety evaluations of radioactive waste disposal systems, this concept has not yet been introduced in many published national regulations and guidelines. On the other hand the safety functions concept is already mentioned in a number of documents recently published by international organisations.

5.2.1 International level

The use of safety functions for the description of the contributions of the main system components in the presentation of the assessment basis is recommended in the NEA Safety Case brochure [NEA, 2004].

The IAEA Safety Standards for Geological Disposal of Radioactive Waste [IAEA, 2006] mention requirements for multiple safety functions: *"The natural and engineered barriers shall be selected and designed so as to ensure that post-closure safety is provided by means of multiple safety functions. That is, safety shall be provided by means of multiple barriers whose performance is achieved by diverse physical and chemical processes. The overall performance of the geological disposal system shall not be unduly dependent on a single barrier or function."* The Standards also mention requirements concerning containment and isolation of the waste.

5.2.2 National regulations and guidelines

The regulations concerning radioactive waste disposal are currently being revised in various countries of the European Union. This means that in many cases the published regulations are becoming obsolete and that non-official information, e.g. discussion documents, presentations at workshops and minutes of working group meetings, is available on the new regulations that are in preparation.

The old **French** regulations [DSIN, 1991] were based on the multi-barrier principle, but they also mentioned, without using the term, a number of safety functions that have to be fulfilled by the repository system: *"the site and the artificial barriers should play a double role: protect the waste by hindering flow of water in contact with the waste and intrusive human actions, and limit and retard the transfer of radionuclides released by the waste to the biosphere during a period necessary for a sufficient radioactive decay of the radionuclides"*. Recently the French nuclear safety authority ASN has published new regulations [ASN, 2008]. The regulations state that the principle of defence-in-depth has to be applied by introducing successive defence lines to prevent or to limit the consequences of releases of radionuclides from the repository system. To ensure that the successive defence lines will be available after closure of the repository complementary safety functions are attributed to the components of the repository system. The identified safety functions are:

- prevent the circulation of water in the repository;
- contain the radioactivity in the repository system (by avoiding the dissemination of radioactivity, by limiting the release of radionuclides and by ensuring a very slow migration through the host formation);
- isolate the radioactive waste from man and the biosphere so that the repository system safety shall not be affected significantly either by erosion phenomena or ordinary human activities.

In **Belgium**, regulatory requirements and guidelines concerning long-term safety of high-level waste disposal are still in preparation. The so-called "Franco-Belge" document [FANC, 2004], which was prepared by the French and Belgian nuclear safety authorities and nuclear waste agencies, recommends that the principle of defence-in-depth should be implemented by multiple safety functions. The safety functions mentioned are isolation, containment and limitation and retardation. The concepts of multiple safety functions and of multiple barriers should be considered as complementary.

In **Germany** the management of radioactive waste is under review. Also the current regulations of geological disposal [BMI, 1983] are being reviewed by the Federal Ministry of the Environment. In this context, GRS Köln has prepared a discussion document on safety requirements [Baltes, 2006]. This document proposes “confinement” as the primary safety function. Further it gives a number of basic and site specific safety requirements.

The **Swedish** regulations [SKI, 2002] mention barriers and their functions: "The function of each barrier shall be to, in one or several ways, contribute to the containment, prevention or retardation of dispersion of radioactive substances, either directly, or indirectly by protecting other barriers in the barrier system."

The **Swiss** regulations [HSK, 1993] mention a system of multiple passive safety barriers, which have to contribute to the containment and retention of radionuclides.

In the **UK**, regulations [EA, 2009] require a multiple barrier concept. This, together with the types of waste in the UK, means that the safety case takes a multi-barrier approach, with explanation of the safety functions provided by the barriers and how these evolve over time. Also, the focus of UK regulations is on limited and delayed releases rather than on absolute containment - there is no regulatory requirement to contain radionuclides for a specified length of time.

5.3 Terminology

5.3.1 Definitions of safety function

The IAEA Safety Glossary [IAEA, 2007] gives as definition for a safety function: *"a specific purpose that must be accomplished for safety"* (the further explanations given in the IAEA Glossary are related to reactor safety and are not directly applicable to a geological repository).

The following definitions are used by waste agencies:

- Belgium [ONDRAF, 2007]: *"function that the disposal system should fulfil to achieve long-term safety"*.
- Sweden [SKB, 2006]: *"role through which a component contributes to safety"*.
- France [Andra, 2005]: *"consists of meeting the safety objectives by implementing different type of actions that all contribute to the safety of the repository during the different phases of the repository".*
- Switzerland [NAGRA, 2002]: *"a function relevant to long-term security and safety".*

In Germany, the following definition is proposed by the technical support organisation GRS [Baltes, 2007]: "a safety function is a function, which takes over safety relevant requirements, in a safety related system, subsystem or single component".

From the above given definitions it appears that the differences in the definition of safety functions are small, and, consequently, that there is a common understanding of the safety functions concept among the different groups involved with safety cases of geological repositories.

5.3.2 Related definitions

Within the national waste management programmes various terms derived from or related to safety functions are used.

ONDRAF/NIRAS uses the term "sub-safety function": it forms a sub-category of a safety function.

SKB uses the term "safety function indicator": it is a measurable or calculable quantity through which a safety function can be quantitatively evaluated. The use of this term has been discussed further in the topic ‘Safety and Performance Indicators’.

ONDRAF/NIRAS uses the term "effective safety function": it is a safety function that is effectively fulfilled during a certain timeframe, and that can thus be relied upon in safety assessments.

ONDRAF/NIRAS and Andra use "latent safety function": it is a safety function that is available in the disposal system, but that only becomes effective if another safety function fails to be fulfilled.

ONDRAF/NIRAS uses the term "supplementary safety function", which is identical to the term "reserve safety function" used by Nagra: a safety function that could be effective during a certain timeframe, but whose performance cannot be properly evaluated because of a lack of knowledge.

Andra uses the terms "reserve safety function", which is a safety function that remains available, possibly in a degraded form, after the period assumed by the designer, and "performance margin" when the performance level is better than the one taken into account by the designer.

5.4 Methodology

5.4.1 Categories of safety functions

In the contributions produced within IP PAMINA (Table 2), and in the Swedish [SKB, 2006] and Swiss [NAGRA, 2002] safety cases that were also considered, three main categories of safety functions can be distinguished:

- stability /isolation;
- containment (called "isolation" by SKB and Posiva);
- limited and delayed releases.

It has to be noticed that in France "prevention of water circulation" is also considered as a safety function [Andra, 2005] [ASN, 2008]; it can be noticed that ONDRAF/NIRAS [ONDRAF, 2007] considers this term as a sub-safety functions belonging to the "limited and delayed releases" safety function.

The importance that is given to a specific safety function strongly depends on the host formation. In case of disposal in hard rock or salt formations, "containment" may be the primary safety function, whereas in the case of disposal in argillaceous formations the safety function "limited and delayed releases" may be at the same level of importance as "containment". The relative importance of the safety functions also varies with time.

a) Stability /isolation safety function

In this group of safety functions it is possible to distinguish two sub-groups:

- one sub-group is related to isolating the waste from future surface events and climate changes, and which thus contributes to the stability of the repositories' near field conditions and to the longevity of the natural barriers; this sub-group forms a boundary condition that ensures that the other safety functions can fulfil their role during the demanded periods; this sub-group is also called, e.g. in Germany, stability;
- the other sub-group is related to the reduction of the probability that future human actions might result in inadvertent intrusions into the sealed repository.

b) Containment (called "isolation" by SKB and Posiva)

This safety function prevents groundwater from coming into contact with the waste. It is considered by SKB and Posiva as the primary safety function. In the case of disposal in hard rock or argillaceous formations this safety function is provided by a metallic canister (also called overpack or container in other waste management programmes). However, in the case of disposal in salt formations the "containment" function is provided by the host formation itself.

c) Limited and delayed releases

The containment function cannot be provided over all relevant times for all radionuclides. After failure of the "containment" function, the "limited and delayed releases" safety function will have to play its role. In the case of disposal in argillaceous formations and some hard rock formations this safety function is a very important one. Therefore, several waste management agencies considering disposal in clay have developed sets of sub-safety functions for this safety function, which are specific to the considered host formation and repository design. Andra developed the following set of sub-safety functions: limiting release of radionuclides, and delaying and reducing migration of radionuclides. ONDRAF/NIRAS considers the following sub-safety functions: limitation of releases, limitation of water flow, and retardation.

5.4.2 Demonstration that the safety functions will be fulfilled

As safety functions are playing an important role in the safety case, methods are developed to demonstrate that the expected set of safety functions will be available as long as required. For this purpose, SKB [SKB, 2006] has developed a set of safety function indicators for its two main safety functions "isolation" (which we call "containment" in this chapter) and "retardation". Those safety function indicators are based on the understanding of the properties of the components of the repository system and quantitative criteria have been defined for each safety function indicator.

ONDRAF/NIRAS has developed a system of so called "safety statements" which have to be fulfilled to ensure that the safety functions will be available at the required time periods. These safety statements are derived from the requirements on the disposal system as a whole, the various subsystems and the individual system components.

For Andra, each safety function is characterised by a performance level, the period during which the function has to be available and the component(s) that have to fulfil the function. Some indicators allowing assessment of the performance of individual components with respect of their safety functions have been defined.

5.4.3 Role of dilution

Dilution clearly plays a role in the estimation of radiological consequences (e.g. doses). However, it is not considered as a safety function because it cannot be controlled by design and only to a limited extent by site selection. Furthermore, it is expected to change considerably with time, e.g., due to the impact of the evolution of the climate on the hydrogeological system.

5.5 Applications and experience

Safety functions were initially introduced in safety cases for implementing the defence-in-depth principle. Therefore, the functioning of the repository system is analysed by identifying the role of the main components and processes of the system. As safety functions facilitate explanation of the functioning of the repository system in easily understandable terms, they soon appeared to be a very useful tool for communication to non-technical audiences. Later on, they started to play a central role in the safety case and they were also used for various applications such as determination of the safety strategy, development of the repository concept, structuring the safety case and identification of a comprehensive set of evolution scenarios.

The following list gives an overview of the applications of safety functions by a number of waste management agencies and technical support organisations:

- determination of the safety strategy: ONDRAF/NIRAS, Andra, SKB, and Nagra;
- developing the repository concept: ONDRAF/NIRAS, NRI/RAWRA, Andra, SKB, and Posiva;
- analysis of the functioning of the repository system: ONDRAF/NIRAS, Andra, SKB, NRI/RAWRA, Posiva, and NDA;
- testing the robustness of the repository system: Andra and GRS-K;
- structuring the safety case: ONDRAF/NIRAS, Andra, Nagra, and SKB;
- scenario identification: ONDRAF/NIRAS, SKB, Andra, and GRS-Köln;
- uncertainty analyses: Andra and ONDRAF/NIRAS;
- identification of performance indicators: ONDRAF/NIRAS, Andra, NRI/RAWRA, Nagra, and GRS-Braunschweig;
- communication: ONDRAF/NIRAS, SKB, Nagra, Enresa, and NRI/RAWRA.

The use of safety functions in safety cases of geological repositories is relatively new. Thus in several national programmes the set of safety functions is not mature and comprehensive.

5.6 Developments

A number of the possible applications listed in section 5.5 are still in an early stage of development.

SKB [SKB, 2006] mentions that some criteria used for the safety function indicators might be relaxed or that other criteria might be added. In Belgium, ONDRAF/NIRAS is under-pinning the set of safety functions by sub-sets of safety statements. Those safety statements require further testing and checks for completeness, and they still have to be complemented with criteria for testing that the safety statements will be fulfilled by the repository system.

Safety functions have already been used by SKB [SKB, 2006] for the identification of scenarios. Other organisations, such as ONDRAF/NIRAS, Andra and GRS, are still testing this possible application of safety functions. For instance, the treatment of the gas issue in the set of safety functions is not evident. A topic strongly related to scenario identification is uncertainty management. The use of safety functions for uncertainty management is being explored by, e.g., ONDRAF/NIRAS and Andra.

As safety functions are playing a paramount role in the Belgian safety case for geological disposal, SCK/CEN developed and tested performance indicators quantifying the contribution of each safety function to the overall performance of the repository system in PAMINA WP3.4 "Safety and performance indicators" [Becker, 2009].

5.7 Conclusions

The term safety function was already used in safety studies of nuclear power plants around 1980. In the defence-in-depth concept for nuclear power plants, safety is based on a set of safety functions. Around 1995 safety functions were introduced in safety cases for geological repository systems for radioactive waste disposal.

Several regulations published in European countries do not yet explicitly mention safety functions and they often refer to the multi-barriers concept. On the other hand they use terms such as containment, and limitation and retardation of releases, which we now call safety functions. Furthermore, it appears from available discussion documents that in several European countries new regulations are in preparation, and that it can be anticipated that many of those new regulations will make explicit use of the multiple safety functions concept. This is already the case for the new French regulations that were published in 2008 [ASN, 2008].

Several definitions of the term safety function can be found in national or international documents, but they all have a very similar meaning. However, for the definitions of secondary terms derived from safety functions (such as the safety function indicators) some homogenisation might be desirable.

The sets of safety functions that are used by most waste management organisations as well as regulators are very similar. Three main categories of safety functions can be distinguished; these are stability/isolation, containment (which is called "isolation" by some organisations) and limited and delayed releases. The importance of a category of safety functions depends on the considered host formation and repository concept. Methods are being developed to demonstrate that the safety functions will be available when required. Dilution in the aquifers and biosphere is not considered as a safety function.

Safety functions are already widely used for various applications such as determination of the safety strategy, development of the repository concept, analysis of the functioning of the repository system, testing the robustness of the repository system, structuring the safety case, scenario identification, identification of performance indicators, and communication. There is a clear trend to increase the use of safety functions within the Safety Case, as can be seen in recent safety assessment exercises.

Topics that are still under development are the derivation of criteria to demonstrate that the safety functions will fulfil their expected role at the required times, performance indicators quantifying the contribution of each safety function, and the application of safety functions for uncertainty analyses. These issues are covered in Chapter 6 (Safety indicators and performance/function indicators) and Chapter 13 (Uncertainty management and analysis) of this handbook.

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6. Safety indicators and performance/function indicators

6.1 Introduction and background

Measures for quantifying the results of performance assessment calculations, mainly dose and risk, have always been used. However, there is a wide international consensus today that it is necessary to use complementary indicators to improve the understanding of the system and to support the safety case. The long-term repository safety cannot be reduced to one single numerical measure and should at least be assessed using several independent indicators, which are called safety indicators. Other indicators are used to quantify or demonstrate the performance of subsystems or single barriers, or of the total system with respect to more specific aspects. Different names are in use for these indicators, such as performance indicators, function indicators, secondary safety indicators or safety function indicators. A unique and internationally accepted terminology does not exist at present.

While there is a consensus that using different indicators in addition to dose or risk in performance assessments is a good way to support the safety case, the different concepts and perceptions vary between the countries and organisations. Since the idea arose some ten years ago, national and international research programmes have led to these different views. Two international projects should be explicitly mentioned in this context:

- The IAEA Coordinated Research Programme on Safety Indicators (1999 – 2003) that produced Tecdoc-1372 [IAEA, 2003]
- The SPIN project (Testing of Safety and Performance Indicators) within the 5th EURATOM framework programme (2000 – 2002) [Becker, 2003]. The participants in SPIN were COLENCO, GRS, Enresa, NAGRA, NRG, NRI, SCK/CEN and VTT.

The IAEA CRP was mainly aimed at creating a database of measured natural concentrations of radiologically relevant substances in materials from different geographical areas, as well as fluxes of such substances between geological compartments, showing their spatial variability. From this database 'safe' values were established for comparison with calculation results. In the SPIN project several numerical measures were identified as safety and performance indicators and tested for their usability in performance assessment by re-doing the calculations of a number of recent national studies.

Although it was intended to keep the concepts developed in these two programmes compatible, this was not possible. Moreover, additional concepts using similar terms have been introduced in some countries and partially adopted by others. All these concepts have been interpreted and refined independently by individual organisations in view of their specific needs and perceptions during recent years. This is the reason why today there is a considerable in-homogeneity of views and understanding of this topic between different organisations. The differences and commonalities are presented in this chapter.

6.2 Regulations and guidelines

Numerical performance assessment is generally accepted as the most important means for assessing the long-term safety of repositories, and therefore, it is subject to detailed formal regulations in the various countries. Such regulations normally make use of at least one typical safety indicator such as dose or risk. The existing national regulations differ in their level of detail and in some countries the regulators are currently revising them. An overview of the regulations regarding **safety indicators** in various countries is given below.

In the **UK** there is a specific requirement that individual risk should be below 10^{-6} yr^{-1}. There is also a general requirement to look at indicators other than dose or risk, and additionally at qualitative safety arguments.

In **Belgium** there is currently no specific regulation for the disposal of radioactive waste. The general rules for protection against ionising radiation (2001) require a maximum dose limit of 1 mSv/yr for members of the public and 20 mSv/yr for workers.

In **Spain**, a regulation of 1987 requires that the individual risk should be below 10^{-6} yr^{-1}, which is directly associated to a dose constraint of 0.1 mSv/yr.

In the **Netherlands** there is a requirement that a safety report has to show that risks and individual doses are below the regulatory limits. These limits are defined for different scenario probabilities and different groups of people (adults/children). The limits lie between 0.04 mSv/yr and 40 mSv/yr for adults and between 0.015 mSv/yr and 15 mSv/yr for children. Moreover, the individual risk due to the releases from a repository must remain below 10^{-6} yr^{-1}.

In the **Czech Republic** it is required that the individual dose rate originating from the repository remains below 0.25 mSv/yr for normal evolution scenarios and below 1 mSv/yr for less probable “emergency scenarios”. There is a regulation on general Environmental Impact, which will be additionally applied in performance assessment, addressing the impacts on flora and fauna, soil, water, etc.

In **France** the basic safety rules require that the radiological impact of a repository to the environment be limited to levels that are as low as reasonably achievable (ALARA principle). The individual dose rate must not exceed 0.25 mSv/yr for the reference scenario, associated with certain or highly probable events. For situations considered as altered, the calculated impact is assessed according to the likelihood of the situation, the chronic or timely character of the exposures, the degree of pessimism of the calculation assumptions.

In **Germany** there is currently no legal regulation for the assessment of the long-term safety of repositories, but there is an official guideline that the individual dose rate originating from a sealed repository must not exceed a value of 0.3 mSv/yr. A supplementary regulation defines the time frame for which the dose rate should be evaluated to 10 000 years.

Finland has the most detailed regulations of the countries participating in PAMINA [STUK, 2001]. The individual dose rate must remain below 0.1 mSv/yr for the most exposed members of the public and “insignificantly low” for others, within an assessment period that is adequately predictable by means of given assumptions about exposure pathways, human habits, etc. For long time frames beyond adequate predictability, constraints for the average release of specific radioactive substances from the geosphere to the biosphere are specified. Moreover, it is required that the repository shall not affect flora and fauna, which is to be demonstrated by assessing the radiation exposure of typical terrestrial and aquatic populations. Finally, it is required that the safety concept be based on redundant barriers, which should be assessed by means of adequate indicators.

In several countries the regulations are currently being revised. In France the Basic Safety Rule of 1991 [JORF, 1991] is under revision, taking account of recently developed safety approaches. In Belgium a regulatory framework for disposal of radioactive waste is being developed. In Germany the guideline of 1983 is being replaced by a new one, which is still under intense discussion. This guideline will require the evaluation of several independent safety criteria.

As a summary, the regulations of the different countries always establish at least one **safety indicator** for which an acceptance criterion is defined. The situation of **performance indicators** is quite different, since most regulations include no requirements on performance indicators. Performance indicators are usually selected and used by the implementers when building the Safety Case to understand, quantify and present to different audiences how the disposal system works.

6.3 Terminology

The terminology used by the different organisations is rather inconsistent. This means that identical or very similar concepts are sometimes denoted differently, while in other cases the same term is used with different meanings. Some formal definitions of the basic terms exist and are generally accepted, but these are interpreted differently by different organisations.

6.3.1 Safety indicator

Within the context of PAMINA ‘safety’ is understood to refer exclusively to the long-term safety of repositories, i.e. passive safety during the principally unlimited post-operational period. The term “safety” itself, however, is not clearly defined in a way that allows a principally unique decision whether or not a repository is safe.

IAEA definition

There is a definition of the term “safety indicator” in the IAEA Safety Glossary [IAEA, 2007]:

“Safety Indicator: A quantity used in assessments as a measure of the radiological impact of a source or practice, or of the performance of protection and safety provisions, other than a prediction of dose or risk.

Such quantities are most commonly used in situations where predictions of dose or risk are unlikely to be reliable, e.g. long term assessments of repositories. They are normally either:

(a) Illustrative calculations of dose or risk quantities, used to give an indication of the possible magnitude of doses or risks for comparison with criteria; or

(b) Other quantities, such as radionuclide concentrations or fluxes that are considered to give a more reliable indication of impact, and that can be compared with other relevant data".

This is a rather general definition which is not specifically made for repository safety. It only refers to radiological safety and does not speak of reference values, but only of comparison with "other relevant data".

There is a consensus about this definition for use in repository PA:

- The wording should not be understood to exclude dose and risk from being safety indicators.
- The limitation to radiological impacts results from the field of responsibility of IAEA but is not always justified for repository PA since chemotoxical aspects can also be addressed by means of safety indicators.

SPIN definition

In the SPIN project a more precise definition was given for the project's purpose:

"A safety indicator must

- Provide a statement on the safety of the whole system
- Provide an integrated measure describing the effects of the whole radionuclide spectrum
- Be a calculable time-dependent parameter
- Allow comparison with safety-related reference values".

Unlike the IAEA definition, this definition clearly requires comparability with safety-related reference values, which means that, e.g., comparability between different options or repository types does not suffice to make a proper safety indicator.

This more precise definition describes the kind of safety indicators considered in SPIN. While some organisations find it too weak for their current work, it is considered too restrictive by others. Discussions during IP PAMINA showed that it would be hard to reach an agreement on a common definition for the "safety indicators", because each organisation uses this concept with its own shades, which makes harmonisation difficult. Some organisations, such as GRS-K, are interested in developing the concept of "safety indicators" in more detail while others consider that a broad definition is enough.

Therefore, in view of the apparently different perceptions, it is strongly recommended that the term 'safety indicator' is not used without clearly stating what is meant.

6.3.2 Performance indicator, function indicator, safety function indicator

The use of the terms "performance indicator" and "function indicator" is rather inhomogeneous and there is no clear distinction between the two. The term "safety function indicator", however, has been introduced by SKB and denotes a characteristic measure for the integrity of a barrier that can be compared with a given technical criterion. Use of this term is generally restricted to SKB concept.

IAEA definition

The IAEA Safety Glossary gives a very short definition of performance indicator:

"Performance indicator: Characteristic of a process that can be observed, measured or trended to infer or directly indicate the current and future performance of the process, with particular emphasis on satisfactory performance for safety".

If "process" is understood to mean not only particular physical or chemical processes but also the evolution of system components or even the total system, this definition seems to be in line with what the PAMINA participants have in mind. It is, however, not very precise and still allows a variety of different interpretations.

The term "function indicator" is not defined in the IAEA Safety Glossary.

SPIN definition

In SPIN a more precise definition of the term "performance indicator" was given for the specific purpose of the project:

"A performance/function indicator must:

- Provide a statement on the performance of the whole system, a subsystem or a single barrier
- Provide a nuclide-specific or integral measure
- Be a calculable, time-dependent or absolute parameter
- Allow comparison between different options or with technical criteria
- Illustrate the functioning of the repository system".

This definition allows a wider variety of quantities to be used as performance indicators, compared with safety indicators. The main difference, however, is that no reference value is required that allows an assessment of safety, but only comparability between different options or with technical criteria. This includes the kind of indicators introduced by SKB to assess the compliance of barriers with technical criteria, called "safety function indicators", even if some of them are not the outcome of PA calculations.

6.3.3 Individual views

In the following the specific views of some organisations concerning the understanding of the terms in question are described in more detail.

Andra and IRSN (**France**) indicators are in line with the SPIN definitions. The only safety indicator used so far is the individual effective dose per year within the context of a predefined biosphere and critical group, as well as a reference value of 0.25 mSv/yr. Performance indicators are understood to assess specific functions of the disposal system. Several such indicators are used in the recent safety evaluation Dossier 2005 Argile [Andra, 2005].

Enresa (**Spain**) adopts the SPIN definitions and considers the annual effective dose as the main safety indicator. Moreover, the activity leaving the near field in a year is compared with the natural activity in a certain amount of natural soil, to show that radionuclide releases to the biosphere due to the repository are negligible compared with natural radioactivity.

Additionally, Enresa uses a number of different performance indicators. Some of these are time-dependent, such as activity fluxes, while others are not, such as travel times or retardation factors of radionuclides through barriers. Performance indicators are primarily understood as indicators for the functioning of individual barriers.

NRG (**Netherlands**) provides no definition but seems to follow SPIN. Dose and risk are the basic safety indicators. Closure times of plugs and seals are used as performance indicators for a repository in salt. The Dutch probabilistic safety study PROSA mentions the term relevant characteristics, indicating parameters such as glass dissolution rate, internal rise rate of a salt dome, groundwater velocity, distribution coefficients, and dose conversion factors.

NIRAS/ONDRAF and SCK/CEN (**Belgium**) follow largely the SPIN definition. The main safety indicators are the individual effective dose and the radiological risk (defined as the product of probability of exposure and the probability of a harmful effect on human health). Additionally, some indicators are defined that are supposed to be "complementary" to dose and risk and are called performance indicators for the safety functions. These indicators allow evaluation of the global and partial performance of the disposal system and the long-term safety functions.

DBE TEC (**Germany**) accepts the SPIN definitions. For defining indicators they propose to follow either a top-down approach starting with legal regulations and deriving technical criteria, or a bottom-up approach defining comprehensive indicators that directly assess the fulfilment of regulations. DBE TEC remarks that even on the regulatory level there is no unique view of the terms. Performance indicator and function indicator are used synonymously.

Posiva (**Finland**) distinguishes between *primary safety indicators* (PSI) and *complementary safety indicators* (CSI). The former refer to the radiological impact of the total repository system, including the biosphere path. The annual effective dose is the only PSI considered and practically the only indicator that fulfils this definition. Complementary safety indicators can be quantitative (numerical) or qualitative and can refer to the total system or a part of it. The radionuclide-specific flux from the geosphere to the biosphere is considered the most important CSI. The terms performance indicator and function indicator are considered unclear and not used. It is stated that unique definitions of all terms are needed.

FANC (**Belgium**) holds a more general view. According to them, a safety indicator should be considered as a key piece of information for the decision making process in order to proceed to the next step. It should assess the level of implementation of the safety strategy, addressing either the whole disposal system or a part of it. Comparability with reference values is not considered as a requirement. Dose and risk comply with this definition. The terms performance indicator and function indicator are not used.

NRI (**Czech Republic**) understands the term safety indicator to denote a value derived from natural concentrations or fluxes of radionuclides. Dose calculations are compared with two values, called bottom safety indicator and upper safety indicator. Performance indicators are understood in the sense of SPIN but have not been used so far.

NDA (**United Kingdom**) considers a range of safety indicators, but gives no formal definition or view of the terms under discussion. In the UK, consideration of qualitative arguments, as well as dose and risk calculations, is expected by the regulator.

GRS-K (**Germany**), the section of GRS that is closely associated with the regulator, has prepared a proposal for a new regulation to replace the old “safety criteria” of 1983. It defines safety indicators to show that the protection objectives are met by an integrated assessment of repository safety, and function indicators to assess the reliability performance of subsystems or components with regard to the requirements. The proposal for a new regulation contains six safety indicators the most of which are not directly related to radiological impact but indicate the containment isolation/containment capacity of the repository system. This concept is based on the perception that biosphere evolution and thus radiological impact can not be predicted on the long term. Consequently, the proof of long-term safety should focus on the safety function “isolation/containment” rather than on radiological impact. GRS-K arguments that protection objectives are met if containment is ensured.

GRS-B (**Germany**), the section of GRS that works for the implementer side, prefers an even more restrictive version of the SPIN definition. A safety indicator should address a specific part-aspect of safety and – as objectively as possible – quantify the respective degree of safety. A safety indicator of this kind makes no sense without a clearly safety-related reference value, and different reference magnitudes can make different safety indicators out of the same calculated measure. Performance indicators are understood in the sense of SPIN and are primarily used for demonstrating the functioning of the system.

The most important differences in the individual perceptions of safety indicators lie in the understanding of what “safety-related” means, as well as in the significance of reference values. Since “safety” is not a unique concept, there are different interpretations. There seems to be a consensus that additional safety indicators should support a single dose or risk criterion, but there are divergent opinions about how safety should be quantified using different measures.

Concerning reference values, the variety of opinions is even wider. While GRS-B holds a very restrictive view and insists on directly safety-related reference value for each safety indicator, Enresa and GRS-K, for example, accept also less strict reference values. NRI does not clearly distinguish reference values from safety indicators. FANC's position is that safety indicators do not require reference values necessarily.

6.4 Methodology

Several organisations have already applied safety indicators other than dose or risk and/or performance/function indicators within their studies. Other organisations are planning to do so in the future. Due to the different conceptual perceptions described in the previous section, the approaches and methodologies differ between organisations. Understandably, organisations that have already used such indicators have more concrete concepts than the others. The participants of SPIN (COLENCO, GRS, Enresa, NAGRA, NRG, NRI, SCK/CEN and VTT) seem to use the outcome of that project as a basis for their concepts.

In general, each approach consists of three steps. The first step is selection of the indicators to be evaluated, the second step is the numerical calculation and the third step is the presentation. This third step is important for conveying the intended message.

In the following, the basic principles of the different approaches are summarised.

The common approach, applied, among others, by Enresa and GRS-B, uses the standard safety indicator, the annual dose, calculated for specific scenarios. This can be done following a probabilistic approach, which means that a number of realisations with stochastically drawn parameter values are calculated and the mean annual dose is used as the safety indicator or following a deterministic approach using a set of constant values for the parameters. In both cases the peak value (of the mean dose or the dose) is compared with a reference value of, e.g., 10^{-4} Sv/yr. For presentation the total dose is plotted together with the contributions of the individual fission and activation products and the four decay chains in order to give a quick graphic impression of the most important radionuclides. Another kind of presentation for probabilistic investigations is to plot the time curves of the mean, the maximum, the minimum and specific percentiles of the dose in one diagram. The maximum and minimum are independent of the selected pdfs and only depend on the parameter ranges.

As an additional safety indicator Enresa calculates the activity flux leaving the far field. It can be used to make different comparisons with the activity present in the natural environment.

A number of performance indicators have also been evaluated, and found useful, by Enresa:

- the canister failure distribution, is seen as useful to describe the expected canister performance,
- the fraction of UOX altered serves as an indicator of the capability of the UO_2 matrix as a barrier,
- the activity flux leaving the near field is an indicator of the capability of the EBS in granite to limit the radionuclide release, and

- the water travel time, the retardation factor of the geosphere and the radionuclide travel time through the geosphere are useful parameters to quantify the capability of the host formation as a barrier.

GRS-B considers, apart from the annual individual dose, the two safety indicators identified in SPIN to be useful. These are the concentration of radiotoxicity in the aquifer (preferably for medium time frames) and the radiotoxic flux from the geosphere (preferably for long time frames). It is regarded necessary to find well-founded reference values that define a safe level for each safety indicator. The concentration of radiotoxicity in drinking water that is deemed to be radiologically harmless is a good reference value that can be easily determined. A suitable reference value for the radiotoxicity flux from the geosphere, however, is harder to find. This flux could be compared with the natural flux in a river near the repository that will finally collect all released radionuclides. Another possible reference value is the natural radiotoxicity flux in the groundwater. Since both reference values address different safety aspects (integrity of river water or integrity of groundwater) they are considered to make different safety indicators from the same calculated quantity. All safety indicators are presented as time curves, possibly normalised to their reference value.

Performance indicators have been used by GRS, following the SPIN methodology, for demonstrating the functioning of the system, which for this purpose is divided into functionally separated parts or subsystems, called compartments. The compartment structure has to be established for every repository system individually, depending on its real structure.

Three performance indicators have been used preferably: the concentrations of radiotoxicity in the compartments, the fluxes of radiotoxicity between the compartments, and the time-integrated fluxes of radiotoxicity from the compartments.

All performance indicators are presented as time curves. The last indicator yields monotonic curves that finally reach an asymptotic value. The differences between these values show how the radionuclides are retained in subsequent compartments.

NIRAS/ONDRAF and SCK/CEN use, in addition to the annual dose, the radiological risk as a safety indicator, which is more suitable for scenarios that cannot be ruled out but have a low probability of occurrence. The risk, however, is not calculated by multiplying the consequences of each scenario with its probability and summing up over all relevant scenarios, but both components are presented separately.

Two indicators of the type that NIRAS/ONDRAF and SCK/CEN call “performance indicators for the safety functions” have been considered in their study: the decayed fractions of the initial inventory activity, calculated for all actinides as well as for all fission and activation products, that is released to the aquifer, and the containment factor: ratio of disposed activity to cumulative released activity into biosphere.

Furthermore, two complementary indicators are given: the total maximum annual activity flux released to the aquifer, compared to the natural alpha activity present in the geological formation, and the total initial inventory of uranium in the waste, compared to the natural alpha activity present in the formation.

The first of these indicators is similar to time-integrated radiotoxicity flux calculated by GRS and yields similar information. The other indicators put some typical properties of the system into perspective with the amounts of natural radioactivity.

Andra uses the annual dose as a safety indicator (as recommended by the French Basic Safety Rule), but performs a detailed system analysis considering three main safety functions of the repository. Each of these functions is addressed through performance indicators. Performance (as used in the dossier 2005 Argile [Andra, 2005]) characterises a function. It is established by the designer according to criteria defined by the users. Among the analyzed indicators are:

- Tthe relation between convective and diffusive flux in the repository and the host rock,
- the overall activity leaving the waste packages, the underground structures and the host rock, as compared to the initial quantity contained in the waste packages,
- the activity flux at each of these components,
- the concentration distributions of dissolved materials in the host rock and in surrounding formations.

Some of them, however, can be presented more as lines of argument than as performance indicators. More specifically for each function:

Resisting water circulation:

- Advective and diffusive flow from the near and far field.
- Distribution of radionuclide masses between the near field (including the shafts) and the far field. This is to show that there is no preferential pathway over the drifts and shafts.

Limiting the release of radionuclides and immobilising them in the repository:

- Analysis of the consequences of early water arrival at the waste allows assessment of the safety function with respect to isolating the waste from water as long as possible.
- Analysis of diffusion and advection in disposal cells via the Peclet number revealed to be adequate to ensure that a diffusive regime was effective in the cell.
- The system capability to limit the release of radionuclides from the waste was assessed by performing a sensitivity analysis against stronger release models.
- Solubility limits of specific elements allow assessment of the retention capability of the waste.

Delaying and reducing the migration of radionuclides:

Three types of indicator associated with the molar flow of each radionuclide are used to assess the performance of the function:

- the maximum molar flow,

- the mass integrally corresponding to the molar flow over the simulation period,
- the appearance time of maximum molar flow.

Comparison of values for each of these indicators, between two different surfaces (S_i and S_{i+1}), helps in assessing the confinement capability of barriers lying between these two surfaces.This concept is in some way similar to the compartment concept of SPIN.

NRI considers the annual dose and puts some effort in determining reference values, different from the regulatory limit, by analysing natural concentrations and fluxes. The values derived in this way are presented together with the annual dose curves and are called “safety indicators”. This is, in a certain sense, in line with the concept of GRS-B, since the reference value is seen as an integral part of the safety indicator, and different reference values make different safety indicators. Performance indicators have not been considered in the Czech concept.

NRG has performed deterministic and probabilistic annual dose calculations. No clear distinction between safety indicators and performance indicators has been made. Instead, the term *relevant characteristics* has been used for calculated safety-related and performance-related parameters.

NDA is planning to investigate several numerical performance indicators, in addition to annual risk calculations, such as radionuclide fluxes. Additionally, a great importance is attached to qualitative arguments, which are considered to be more meaningful for non-technical audiences. Such qualitative arguments can include

- comparison with natural analogues,
- consistency with independent site-specific evidence, such as observations in nature,
- evidence for the intrinsic robustness of the system,
- passive safety features,
- general arguments related to radioactive waste management.

Posiva considers the annual dose as the only “primary safety indicator”. It is calculated for two scenarios, one only considering the drinking water path, the other also integrating watering cattle and irrigating crops. Additionally, it is planned to consider “complementary safety indicators”, which can be quantitative or qualitative. These indicators are not yet specified, but the radionuclide-specific flux from the geosphere to the biosphere is considered the most important one.

FANC has not yet developed a detailed view on the subject but sees the necessity to use safety indicators other than dose or risk to support the safety case and to communicate the system safety to the technical and non-technical public. Safety indicators should provide a quantitative indication of the level of implementation of the safety strategy, but it is not considered necessary that a reference value is available for comparison.

GRS-K has developed a proposal for a new German guideline to replace the old “safety criteria” from 1983 [BMI, 1983]. This proposal contains the following six safety indicators:

- the proportion of the cumulative released quantity of substance over the safety case period (to assess directly the containment capability),
- the concentrations of released uranium and thorium (to assess the modification of natural concentrations),
- the contribution to the power density in groundwater (to assess the modification of natural radioactivity),
- the contribution to the radiotoxicity in groundwater (to assess the modification of natural radiotoxicity),
- the radionuclide concentration in the usable water near the surface (to assess the modification of natural radionuclide concentrations),
- the effective individual dose per year (to assess the modification of natural ingestion of radiotoxicity).

For each of these indicators, individual limits are provided for both classes of likely scenarios and less-likely scenarios.

DBE TEC does not perform its own calculations but emphasises the necessity of distinguishing between the technical and the regulatory level. It is stated that, when defining new indicators for assessing the performance of a repository, different regulatory fields (mining, water protection, radiation protection and their different timescales) and levels should be regarded.

6.5 Application and experience

Only some organisations have experience of calculating and evaluating safety indicators other than dose or risk and/or performance/function indicators. The SPIN participants made some experiences in that project by re-calculating four granite studies and evaluating several safety and performance indicators. It was agreed that these three safety indicators are useful and should be used with preference for different time frames:

- The annual effective dose is best for relatively short time frames up to 10 000 years, but should nevertheless be evaluated over the total assessment period.
- The radiotoxicity concentration in the aquifer is more robust because it is independent of the biosphere uncertainties and should be preferably used for medium time frames up to some hundred thousand years.
- The radiotoxicity flux from the geosphere is still more robust as it is additionally independent of the aquifer uncertainties. It is, however, hard to find adequate reference values. It should be evaluated preferably for long time frames up to millions of years.

Similar conclusions regarding the use of these three indicators and the corresponding time frames had already been drawn by IAEA [IAEA, 2003].

Moreover, it was found that performance indicators provide a good means for improving and communicating system understanding.

Enresa has calculated in the studies for its reference repository concepts the activity released in a year and compared it to the natural activity content of a certain volume of soil. This could be an illustrative measure for communicating the system safety to the public. Additionally, several performance indicators have been calculated. By calculating and presenting the fraction of UOX vs. time it could be shown that even under pessimistic assumptions the matrix would release the total inventory only after several millions of years. Radionuclide travel times show that, e.g., plutonium is unlikely to start to leave the system earlier than 5 million years after repository closure. Enresa experience is that any magnitude that can be useful to understand the system behaviour and to quantify the capabilities of the different barriers to delay and limit the releases of radionuclides from the repository, should be considered when building the Safety Case.

GRS-B has calculated the three safety indicators recommended in SPIN in a national project dealing with the existing Morsleben LLW repository (ERAM). Though the reference values were determined independently it was found that all three indicators yield nearly the same gap of three orders of magnitude between the maximum output and the reference value. This is interpreted as a mutual confirmation of the safety statements. Additionally, some performance indicators have been calculated to illustrate the functioning of the system. Especially the time-integrated radiotoxicity flux was found to give a good impression of the efficiency of the different system components. It could be shown that even the worst of the emplacement areas releases only 10 % of its inventory, the other emplacement areas less than 0.3 %.

NIRAS/ONDRAF and SCK/CEN claims that for longer time frames the safety assessment should be based increasingly on concentrations and fluxes instead of dose or risk, and for very long time frames on qualitative arguments rather than on calculations. In SAFIR-2 [NIRAS, 2001], the annual dose has been calculated for several scenarios and their probabilities have been discussed in a qualitative manner. This is not exactly a risk calculation but a semi-quantitative risk assessment. It is concluded that this kind of investigation is more appropriate than a numerical risk calculation because the scenario probabilities are highly uncertain. Three performance indicators have been evaluated. The decayed fractions of radionuclide inventories are rather small for long-lived weakly sorbed radionuclide, and consequently, large fractions of these reach the biosphere, but spread over long times. Only a very small portion (about 10^{-10}) of the initial total activity, however, reaches the biosphere.

Andra has calculated several performance indicators in association with the performance of functions in Dossier 2005. The migration delay of radionuclides, for example, is illustrated by presenting the molar flows at different points of the repository. It can be seen that the flows at the exit of the shaft are clearly more delayed than those at the top of the host formation. The maximum arrives at the shaft exit after approximately 800,000 years, at the top of the formation after 250,000 years. By evaluation of the attenuation of the maximum it has been confirmed that the host clay formation (Callovo-Oxfordian) has a very good capability for retaining actinides and delaying their release.

6.6 Developments

Several organisations are planning further developments of their methods or test further indicators. Andra will soon revise their safety case and will reconduct the calculation of safety and performance indicators using a similar approach to the one of the dossier 2005. NDA has not yet implemented and applied a methodology but will do that soon.

In IP PAMINA RTDC-3 there was a work package on safety and performance indicators (WP3.4) in which, among others, GRS-B, Enresa, SCK/CEN, NRG, NRI and FANC-BelV were involved. These organisations tried to harmonise their views, at least partially, and performed calculations within their different national studies for a variety of indicators, including risk indicators. Work on the definition of suitable reference values for safety indicators was performed within PAMINA WP3.4, also. The results obtained are presented in PAMINA deliverable D3.4.2 [Becker, 2009].

6.7 Conclusions

There is international consensus that a repository safety case can be enhanced by the presentation of a range of safety indicators, to complement the dose or risk calculations. There are different concepts of assessing repository safety and performance by means of other indicators. Several organisations have experience in using such indicators for supporting the safety case and communicating the results to the technical and non-technical public. In some countries the authorities are planning to revise their regulations and introduce the obligation to consider additional indicators.

The review has shown that there is still a large variety of different views on the exact terminology used for safety indicators and performance/function indicators. The project participants recognised this and felt it was not a serious issue as long as the terms were clearly explained in each safety case.

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7. Analysis of the evolution of the repository system

7.1 Introduction

A deep understanding and a good description of the evolution of the repository system are indispensable requirements, and the first steps, for setting-up a safety assessment as part of safety case. This deep understanding should never be understood as a “precise knowledge or prediction” of the future events that will take place along the time frame considered in the assessment.

The future evolution of the repository system is inherently uncertain and could follow diferent paths, what it leads in a natural way to the concept of scenario. The concept of safety functions (chapter 5), the use of qualitative arguments in addition to quantitative assessment and the notion of integrated analysis have influenced methods for description of the disposal system and the development of scenarios.

The recent work made by different European organizations participating in the project for the description of the disposal system and its link with the derivation of scenarios will be illustrated in this chapter.

7.2 Background

The repository system varies from one country to other, and thus the analysis of its evolution, and is highly conditioned by the respective national context (chapter 3).

Various types of rock are currently being investigated. Two organisations consider a clay host rock formation for implementing a repository (Andra , SCK/CEN/ONDRAF/NIRAS) and based their contribution accordingly. Three organisations based their contributions from studies on granite formation as a host rock (Enresa , NRI, and Posiva). Two organisations present their approach for a salt rock formation (GRS-B and NRG) One organisation doesn’t describe a site specific approach (NDA) as the UK is just at the beginning of a site selection process.

As will be indicated in the following sections, the progress in the project may have some influence on the approach chosen to analyse the repository evolution, and on the development of specific FEPs database and their organisation.

7.3 Definition

The working group agreed to define the Analysis of repository evolution as:

- identification and study of processes (THMCR-G) effects and influences of waste and repository induced phenomena, of the site, of external events or features (natural phenomena, or human induced phenomena) plus

- predictions of potential evolutions of site and repository (link with modelling topic), including influences of any disturbances (natural or human induced).

7.4 Regulatory requirements

Requirements from authorities provide guidance that implementers have to conform to. Such regulations may stipulate dose, and/or risk values to be respected, but they may also have specific request relative to the analyses of the evolution of the repository system.

Existing regulations may vary from no specific requirement to very detailed one that may constrain timeframes and/or may request taking into account specific FEPs (internal or external), and/or specific scenario with different level of detail. It is to note that regulatory requirements and guidelines concerning long-term safety of high-level radioactive waste disposal are still in preparation in Belgium (SCK.CEN, ONDRAF/NIRAS). As well, in England, regulations are currently being discussed (NDA).

They can be summarised as:

1. No specific regulatory requirements or guidelines regarding how to analyse the evolution of the repository system (Enresa, NDA, NRG).

In Spain, there are no specific regulatory requirements or guidelines regarding how to analyse the evolution of the repository system. Only acceptance criteria for radioactive waste final disposal facilities, established by the Spanish Regulatory Body (CSN), was set in 1987 in these terms: *"to ensure safety, individual risk should be smaller than 10^{-6} yr^{-1}, that is the risk associated to an effective dose of 10^{-4} Sv/yr"* (Enresa). In the Netherlands, a central policy consideration of the Dutch Government is a stepwise approach to finding waste management options that are feasible, suitable and acceptable, in both technological and societal respects. It is based on three policy documents, published respectively in 1984, 1993 and 2002. There are presently no regulatory requirements and provisions that directly relate to the topic of "evolution of the repository system". The Dutch CORA program however investigated the effects of glaciations on the safety of a repository (NRG).

2. Regulations identify the necessity of evaluating the repository evolution but do not provide specific guidelines on how to do it (NRI).

The safety analyses, used for the preparation of safety reports, require according to SONS/SÚJB guide, the evaluation of repository evolution, but it is not exactly defined how this evaluation should be done. In the Czech DGR programme, analyses of the evolution of a repository are closely connected with other topics of post-closure safety analysis approach.

3. Regulations contain some requirements and statements that have a direct impact on the assessment of the evolution of a repository system (GRS-K, GRS-B, IRSN, Andra, and Posiva, although the German regulations currently undergo a thorough revision -GRS-K).

These requirements and guidelines may be summarized as follow:

- To justify (or show) a good understanding of the processes having influences on the evolution of the repository system (Andra - IRSN). Requirements will focus on :
  - Modelling accounting for disturbances induced by the repository (THMC, gas...) including during the operational phase,
  - Modelling the evolutions of the system for scenarios development, either for reference scenario (taking into account highly probable natural events, and repository induced processes), or altered scenario (less likely events),
  - Modelling the radionuclides migration in order to evaluate the impact on man and the environment.
- To take into account a series of FEPs in scenarios, expected evolution or alternative evolutions resulting from internal or external FEPs (endogenous and exogenous) including human actions (GRS-K, Posiva, and Andra). Scenarios should consider features, events and processes which are potentially significant to long term safety. In some cases, possible evolutions of the repository system have to be distinguished according to their probability, as the probability defines the way how to deal with an evolution of the repository system and its consequences (GRS-K and GRS-B).
- To give recommendations on timeframes to be considered. Some time period for safety assessment are given in the German regulations. As well, some timescale for geological stability, and some specific events such as glaciations, are given in the French regulations but no specific time period for safety assessment (IRSN, Andra). Regulations may also give indications on which repository life phases are to be accounted (construction, operational, after closure...) (GRS-K, IRSN, and Posiva). The timeframes considered in the evolution/s of the repository system will be given by the time at which external events are expected to influence the site and repository (Posiva).

In Germany (GRS-K), a draft report “safety requirement” describes in a more specific way how the evolution of the repository has to be analysed, and what has to be taken into account: the entire spectrum of potential evolutions of the repository system, “*distinguished according to their probability”* has to be taken into account. The assessment of the occurrence probability of relevant factors plays an important role.

In France, the legal basis for licensing is the Planning act of 28 June 2006. The new guide (ex RFS.III.2.f) provides a framework for the studies to be conducted (Andra - IRSN): The protection of man and the environment are to be demonstrated. The 2008 version of the Guide indicates that: [2]“The evaluations will be based on a modelling of the evolution of the storage, in particular of the barriers, of the underground waters circulation, and of radionuclides transfers […]. This modelling has to rely upon a sufficient knowledge of the physico-chemical processes and the events which can affect the evolution of the repository system and its environment and thus on investigations, as well as adapted research program. The models are simplified representations of real phenomena. It is advisable to show, on one hand that these representations do not leave aside important phenomena, on the other hand those simplifications lead to conservative evaluations”. In the annex of the guide, a series of FEPs to take into account is given, including external events such as global

[2] Not an official translation

climate evolution (including glaciations), geomorphologic evolution, human actions (including greenhouse effects), and human intrusion.

In this respect IRSN indicates that: "Site characterization is the first step to highlight the processes and phenomena p*otentially affecting the performance of the repository components and the disposal system as a whole, including the natural evolutions of the components and the interactions between natural and engineered components.* This characterization should thus be co*nducted* on long scales and of scope sufficient to acquire an adequate understanding of the phenomena potentially influencing site safety for the time periods of concern, as well as relevant information to support scenarios for the future probable evolution *of the site and to develop credible physical process models.* The demonstration of this understanding of the probable future evolutions of the disposal system is an important task in the safety demonstration to be supported by in-situ testing, data analysi*s, pertinent modelling, as well as comparison with suitable analogues*".

The Finish regulator STUK, as part of the demonstration of compliance with the safety requirements, states that: "A scenario analysis shall cover both the expected evolution of the disposal system and unlikely disruptive events affecting long-term safety. The scenarios shall be composed systematically from features, events and processes, which are potentially significant to long-term safety and may arise from:

- Mechanical, thermal, hydrological and chemical processes and interactions occurring inside the disposal system
- External events and processes, such as climate changes, geological processes and human actions".

7.5 Place of the analysis of the repository evolution in the strategy

Independently from regulatory requirements, all organisations acknowledge that the safety analysis relies upon a thorough knowledge and understanding of processes and phenomena likely to evolve in the repository and its environment, from the initial stage to the long term. However, the place given to this analysis may vary depending on the overall strategy adopted by implementers (e.g. top-down or bottom up approach, or a mix of both). It was pointed out that analysis of the repository evolution can be a key point in the overall safety strategy for development of a safety case (Andra, Enresa, and NRG), and for safety demonstration (GRS-B).

For most of the organisations, a strong link exists between the analyses of the repository evolution and the scenario (reference or altered) development (NRI, Posiva, SCK.CEN, ONDRAF/NIRAS, NRG, and NDA, Andra). For GRS-K, a regulator: "The analysis of the evolution of the repository system is an inevitable task in order to get more insight how the entire system will behave under *certain circumstances and what the relevant influencing factors are".*

- It is a background for safety analyses. It aims at identification, analysis and conceptualisation of FEPs and their associated uncertainties. The objective is to obtain the relevant FEPs to consider, to analyse them (which include to define the associated analyses), to organise them and then to derive conceptual model (usually limitied to time and space).

- It is a background for definition and assessment of scenarios (reference or altered one). It can be a basis for uncertainty analyses (qualitative safety analyses or quantitative). It aims at identifying which THMCR-G effects or FEPs can affect the safety functions, or the “barrier” and how those FEPs and their associated uncertainties can affect the evolution of the disposal system.
- It can provide information for design studies. For instance, it can describe the evolution with time of the material being used. Design architecture may also be a base for analysis of the repository evolution (breakdown into representative or specific components/barrier).

This list is not exhaustive, each contribution in the annex provide the links of the repository evolution with other topics to consider in the safety analysis. The role of the analylsis of the repository evolution in the safety case can be summed up as follow:

1. Analysis of the repository evolution is a key component of the safety analysis (Enresa, Andra and NRG)

A detailed description of the evolution of the disposal system is a key component of the safety analysis (Andra, Enresa), to show availability and performance of safety functions, provide information for concept design (Andra) and input for safety analyses such as scenario building (Andra).

NRG also considers “Assessment Strategy”, “Safety Approach” as main related topics. They also refer to “Modelling Strategy”.

In the Spanish case, the objective is to confirm that the safety functions provided by the different barriers are fullfilled during the time period expected for each of them. To be consistent, the evolution of the repository components needs to be analysed for the whole time period adopted for the consequence analysis. The identification of the different plausible future evolutions of the disposal system (or “scenarios”) is done in chapter “Definition and Assessment of Scenarios”. Since the analysis of the evolution of the disposal system is studied mainly through modelling, the present topic is strongly related to the modelling strategy (Enresa).

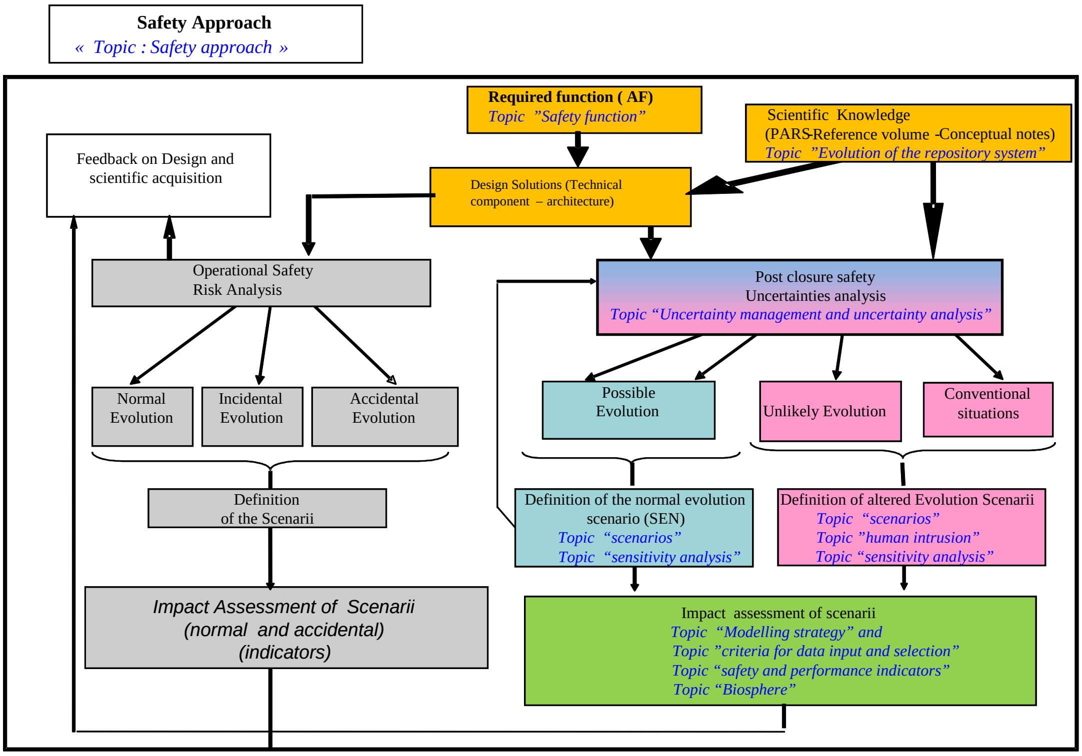

Figure 9 – Scheme of the safety analysis approach of Andra.

For Andra, a knowledge corpus is required to describe the long term behaviour of the repository with a high degree of confidence and to provide a basis for the safety analysis. Indeed, the safety analysis depends first and foremost on thorough knowledge of phenomena liable to evolve in the repository and an understanding of the long term behaviour of the repository and its environment (Figure 9). But, it also provides information for design solutions (simplification and control of the phenomenological evolution were based on various design measures). The architecture of the repository may contribute for instance to simplify comprehension of the thermal and hydraulic processes occurring in the repository. Simplification and control of the phenomenological evolution in the Dossier 2005 were based on various design measures, such as:

- Compartmented and modular repository architecture with distinct and separated reference package repository zones (and distinct and separated disposal modules within each repository zone).
- Minimisation of maximum temperatures in the repository and its geological environment.
- Choice of constitutive materials for the engineered structures of the repository to limit chemical perturbations
- Mechanical dimensioning of the underground engineered structures to limit mechanical damage of the argilites.

In these conditions, the analysis of the repository evolution can be approached almost independently to describe the HLW and IL-LLW repository zones. This very significantly simplifies the study of the consequences of this evolution on radionuclides release. It involves scientific work, experiments results, models and their configuration in the form of a phenomenological analysis. The safety analysis is a tool which, on the basis of in-depth knowledge of the phenomena and uncertainties, determines scenarios and sensitivity analyses to consider.

2. Analyses of the repository evolution are used to derive uncertainties and scenarios. The objective is to obtain the relevant FEPs to consider (NRI, Posiva, SCK.CEN, ONDRAF/NIRAS, NRG, and NDA, Andra).

For Andra and SCK.CEN,ONDRAF/NIRAS, a key element of this phase was the identification, analysis and conceptualisation of the safety-relevant features, events and processes (the FEPs), e.g. by means of site characterization, general knowledge of the underlying mechanisms of the considered processes, identification and development of suitable models and gathering the required data from tests, experiments and scientific literature.

The derivation of the scenarios from the uncertainty analysis of the assessment basis is the one developed in the SAFIR 2 exercise (SCK.CEN,ONDRAF/NIRAS). A distinction between different periods of time in safety assessments is made. Potential evolutions differing from the expected fate of the repository have been studied in the framework of safety assessments of SAFIR 2 (chapter 8). As well, derivation of scenarios from uncertainty analysis is presented by Andra in the Dossier 2005 (QSA) and discussed in chapter 13.

In the NRI/RAWRA strategy, analyses of the evolution of a repository are closely connected with other topics of post-closure safety analysis approach, as outlined in Figure 10. In this case, they are involved mainly in the second stage of safety analysis strategy which covers identification and analyses of FEPs, scenario development, analyses of safety functions and derivation of the assumptions.

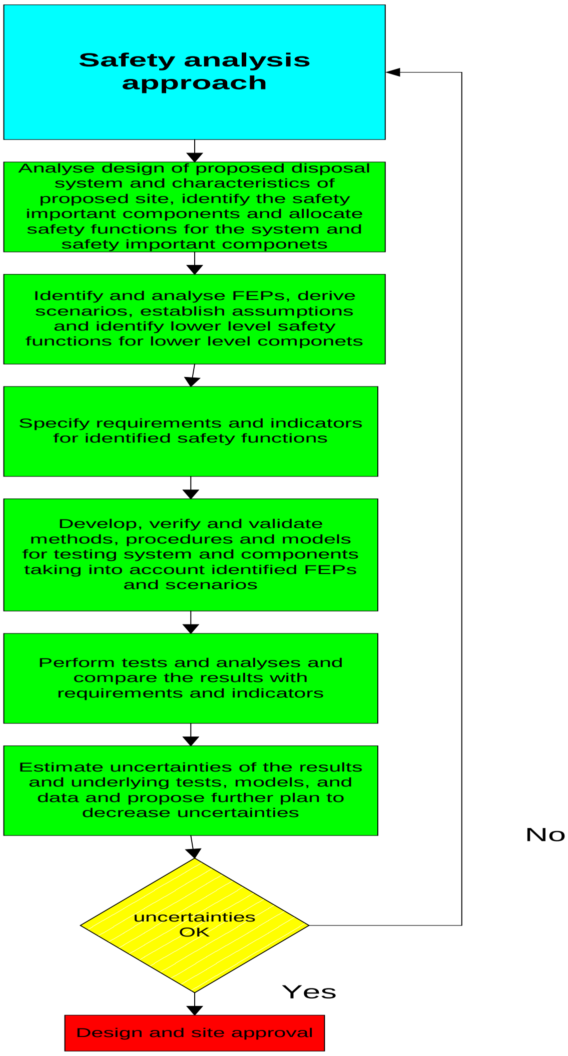

Figure 10 – Scheme of the safety analysis approach of NRI/RAWRA.

In Netherlands, in the late 1980's the VEOS study (Safety evaluation of disposal concepts in rock salt) has been performed with the aim of the evaluation of the post-closure safety of some possible disposal concept and the determination of relevant characteristics. In the early 1990's a generic probabilistic safety analysis (PROSA) of the Dutch generic reference disposal concept was performed. The PROSA methodology was developed for the determination of scenarios for the safety assessment of an underground repository for radioactive waste.

In Posiva's approach, the scenario formulation is to follow a top-down approach (Figure 11), i.e. start from the regulatory safety requirements concerning scenario analysis in YVL 8.4 [STUK, 2001] and then consider how FEPs and associated uncertainties affect the various safety functions of the disposal system and their evolution over time.

HANDLING OF PROCESSES
Category: indicates the relevant sub-system component (e.g. canister) and type of process (evolution or migration related)
General description: provides concise explanation of the process and current understanding of how it operates
Olkiluoto-specific issues: provides a summary of any site specific issues that need to be considered
Uncertainties: overview of main conceptual and parameter/data uncertainty
Time frames of interest: relevance to post-operational, re-equilibrium or glacial period
Scenarios of relevance: relevance of process to climatic scenarios, base scenario or assessment scenarios
Significance: for the long-term containment of radionuclides (RN) within the canister or for RN transport or retention after canister failure
Treatment in performance assessment: how the process is dealt with in RN transport and performance assessment models (implicitly, explicitly)
NEA's equivalent FEP: correspondence of the process to process/es in the NEA international FEP database (NEA 2000)

Figure 11 – Template for the handling of process, process significance and relationship to scenarios of Posiva.

For GRS-K, the "Analysis of the evolution of the repository system" has a strong relation with the "Definition and assessment of scenarios". Hence, this topic comprises the fundamental basis for the scenario development which in turn represents the identification and the selection of relevant alternative developments (scenarios) of the repository system for further treatment in safety analyses. Specific topics which strongly relates to the evolution of the repository system like scenario development, human activities, and biosphere are described regarding their context but are addressed in detail separately in other chapters of this handbook.

3. Analysis of the repository evolution is studied in connection with the safety function via the use of safety statements.

It implies to investigate which effects (THMC – Geochemistry and Gas) can affect the functions. SCK.CEN,ONDRAF/NIRAS, Andra, and Posiva illustrate with their approaches the derivation of scenarios using the functional and uncertainty analyses.

The safety functions were used to define a reference scenario (or normal evolution scenario) and altered scenarios (or divergent/alternative scenarios) by Andra. It allows describing the normal evolution situations for the repository in the post-closure phase, that is, those situations in which the components fulfil the expected functions and which appear to be the most likely. Once the normal evolution is described, the models and parameters are set. The calculations confirm that the proposed concepts effectively fulfil the safety functions which are assigned to them and the individual radiological exposures are acceptable under normal evolution.

A qualitative safety analysis (QSA) was conducted, in which there is a systematic analysis of uncertainties on FEPs and their effects on safety functions. This methodology determines and assesses, component by component and with respect to the safety functions assigned to each, the uncertainties in order to ensure that these uncertainties are taken in account by the design choices, which reduce their effects or they are considered in the normal evolution scenario and, in particular, through sensitivity analyses or in the definition of altered evolution scenarios corresponding to highly unlikely events or to dysfunction of safety functions (the seals failure scenario, the package failure scenario, the bore-hole scenario and a severely degraded scenario which radically lower performances of safety functions). Andra used the NEA FEPs database as a completeness check to ensure that all relevant FEPs were covered by the QSA.

4. Analysis of the repository evolution can be a support to proof safe enclosure as in the case of GRS-B.

In coherence with the regulatory requirements, the proof of safety is based on numerical analyses and a collection of plausible arguments that support the concept for a defined safety level (GRS-B). The safety concept is focussed on the proof of the integrity of the salt formation, which is supposed to guarantee the isolation of the waste from the environment. The function of the engineered barriers is to reseal the disturbed salt rock formation after the closure of the repository and to prevent the inflow of significant volumes of brines into the repository until the convergence of the rock salt seals the man-made voids and cavities and the safe enclosure of the waste is ensured. The approach relies upon scenario development from possible set of FEPs. The safety level and the required grade of isolation have not been defined yet.

7.6 Approach/method used in the description of the evolution of the repository

All the approaches have in common the objectives of:

- Identification and study of processes (THMCR-G) effects and influences of waste and repository induced phenomena, of the site, of external events or features (natural phenomena, or human induced phenomena)
- Estimation of potential evolutions of site and repository (link with modelling topic), including influences of any disturbances (natural or human induced).

The development of the national waste disposal project is for most organisations a stepwise process. The maturity of the project and particularly of the site investigation (including site localisation processes) influences the approach used or developed by the organisations in order to analyse the evolution of the repository.

Some examples show that if the project is generic or at an early stage in the processthe FEPs to consider in the analysis of the repository evolution rely upon international databases.

When a site or a possible area of implantation in a rock formation has been selected, some organisations develop site specific FEPs and concept specific FEPs associated to more and more realistic representation of the system.

Due to the maturity of the project, the regulator requirements, and the maturity of the site investigation, the approaches described by the different organisations can be summed up as:

- Identification and classification of FEPs using a structured FEPs analysis from international databases – Classification may define Super FEPs as for example in the probabilistic approach of PROSA (NRG). This is also the approach of GRS-B, NDA and NRI.
- Well supported detailed modelling: creation of conceptual model based on analysis of FEPs - Scenario cases are defined using international databases, and then conceptual models are created by the analysis of FEPs within a scenario. This is the approach followed by Enresa.
- Phenomenological analyses of the repository evolution: development of site and concept specific FEPs from observations and data acquisition – The approach consists in identifying the possible evolutions of the repository using a sound scientific knowledge of THMCR-G processes for a particular rock formation (Andra, SCK.CEN, ONDRAF/NIRAS and Posiva). International database and FEPs catalogue are used as a check list.

Some general features:

- All approaches identify and study the (Chemical (C), Thermal (T); Hydraulic (H); Mechanical (M); Gas formation (G); Radiation (R)) processes and their interactions between major components of the disposal system. Ccouplings of processes and/or phenomena are mentioned by Andra, Enresa, NRI and .CEN, ONDRAF/NIRAS. Such couplings are still in development but some examples of HM, TH, THM, and G are given in some contributions (see appendix).
- Study the potential evolutions of the site and repository, from the initial state to the long term considering:
  - Potential climatic changes,
  - Repositories induced processes and external events such as glaciations, and human induced phenomena.

Some specific features:

- Timeframes supporting the description of the repository evolution with time can be defined by regulation (Andra ...), but also by specific FEPs (such as climatic and geologic evolution, Posiva) or THMCR-G processes (such as the thermal phase, Andra, SCK.CEN/ONDRAF/NIRAS) or coupling of all the THMC-G processes (Enresa).
- Analysis of the evolution of the repository can consider :
  - the near field, the far field and the biosphere components separately (an example is given by Enresa),
  - a more integrated description on the major components of the disposal system. Recent developments consider more phenomenological approach and breakdown the FEPS into time and space. They propose detailed description of the (THMCRG) processes affecting the system components within specific time frames. Andra

developed the Phenomenological Analysis of Repository Situations (PARS) and ONDRAF/NIRAS developed the so-called “Story Boards”.

- specific FEPs (such as glaciations in the case of Posiva).

Examples of treatments in the safety case extracted from the contribution illustrate the different approaches described in the previous section:

1. A Structured FEPs analysis from international catalogue (GRS-B, NDA, NRI).

The analysis of the repository evolution relies upon a structured FEP analysis which uses national/international FEPs databases. It aims at identification and analyses of relevant FEPs in order to derive scenarios. They may require expert judgement as quoted by NRI. Such an approach was used:

- as guide for internal analysis of the complete system (NRI),
- for probabilistic treatment as, for example, the “probabilistic approach PROSA” described by NRG for the safety analysis of the Dutch generic reference disposal concept. It used the FEP catalogue to show comprehensiveness.

GRS-B: The main objective of the scenario development is the identification of relevant FEPs that affect the future behaviour of the repository system and the synthesis of these FEPs to an appropriate set of scenarios (i.e. calculation cases for PA models). Beside its importance for the scope of the PA modelling procedure scenario development is essential for the communication of the modelling results and its underlying assumptions to the public. For this reason the scenario development has to be as systematically and transparently as possible. In the past two basic approaches have been applied in Germany:

- the identification of all FEPs that can have an influence on the repository system and the emplaced waste and development of scenarios by combining these FEPs to plausible scenarios (bottom-up approach),
- the determination of initiating FEPs for scenarios, in which barrier functions in the repository system are affected in such a way that a contact between brine and waste is possible, and identification of FEPs that are relevant for these scenarios (top-down approach).

The first approach has the advantage to be more objective and traceable, but the step from a complete FEP-list to a set of scenarios has not been accomplished yet without using elements of the top-down approach. For the salt domes in Northern Germany a FEP-list for spent fuel and HLW was generated exemplarily for a reference site taking into account both approaches. The FEP-database developed by OECD/NEA provided the starting point for this FEP-list. Currently the list of FEPs is used for the definition of a complete set of scenarios.

NRI, RAWRA: The approach used for the description of the evolution of the Deep Geological Repository (DGR) system in the mentioned safety case for “Reference design” in granite host rock has been based on expert judgments. The evaluation of the repository evolution was divided into the evaluation of the evolution of external system and the evolution of the internal system. External system is defined in an agreement with NEA-OECD report as a system outside the disposal system domain. External factors affecting disposal system are FEPs with causes or origins outside the disposal system, i.e. natural or human factors of a more global nature. In general, external factors are not influenced, or only weakly influenced, by processes within the disposal system.

NDA: A formal, structured FEP analysis was used to build conceptual models of evolution of repository system. This FEP analysis was also used to compare with international FEP databases, such as that developed by the NEA, to check for completeness.

NRG: The study had two equally important aims: the determination of the radiological effects on humans and the derivation of safety relevant characteristics of a disposal concept for radioactive waste. These characteristics have been derived from sensitivity analyses of the radiological consequences of some disposal concepts in rock salt formations. The PROSA study was restricted to the safety in the post-closure period. The PROSA study used a systematic approach to scenario selection that ultimately led to a set of representative scenarios that covered all aspects relevant for the long term safety. The method used a FEP catalogue to show comprehensiveness of the obtained set of scenarios. Then the features, events and processes (FEPs) were determined that may influence the efficacy of the barriers and thus enables 'transport' through a barrier. Such FEPS can be drawn from numerous lists that over time have been collected by different institutes for specific applications. Starting point for the derivation of scenarios for an underground disposal facility is a broad knowledge of the system, which enables a good description of the development of the facility and its vicinity in a so-called “conceptual model'. In addition, scenarios have to be developed that give an indication about how a repository will evolve in the future, taking into account variations in geology, climate or human operations. The FEP analysis of the evolution of repository systems was backed up by research and expert elicitation of uncertain parameters where appropriate. The methodology implied that each FEP has to be judged carefully in order to establish whether it is of importance and if so how the role will be and in which part of the repository the FEP applies.

2. Well supported detailed modelling: creation of conceptual models from analysis of FEPs

In the Spanish case the engineered barriers systems are well defined for disposal concepts in granite and clay, but there are no preliminary sites selected. A detailed description of the evolution of the disposal system is a key component of the Safety Case. To achieve this goal it is necessary a good understanding of the processes that govern the system evolution in order to be able to make predictions using well supported models. Performance Assessment exercises have been done for “synthetic” sites, created on the base of limited data available for the Spanish favourable areas. As consequence, the analyses of the evolution of the disposal systems done up to now show a higher level of detail on the evolution of the near field, although obviously when a real site becomes available, its future evolution will be studied in depth.

Expert judgement and FEP list from international database allow identifying all the relevant processes that must be included in the detailed modelling to predict the repository evolution (Enresa).

Mostly described by Enresa, the method relies upon a description of the evolution of the disposal systems which is based on the analysis of the FEPs (Features, Events and Processes) identified as relevant during the scenario definition phase of the Safety Case. The description of the system evolution is focused on the key properties of the barriers that contribute to safety. For instance, considering the bentonite, buffer analyses are oriented to justify that material properties, such as swelling capability, hydraulic conductivity, sorption capability, etc. remain within appropriate values for the evaluation time. On the base of these FEPs, conceptual models for the evolution of different parts of the repository are created and translated into mathematical models that allow making predictions (Figure 4).

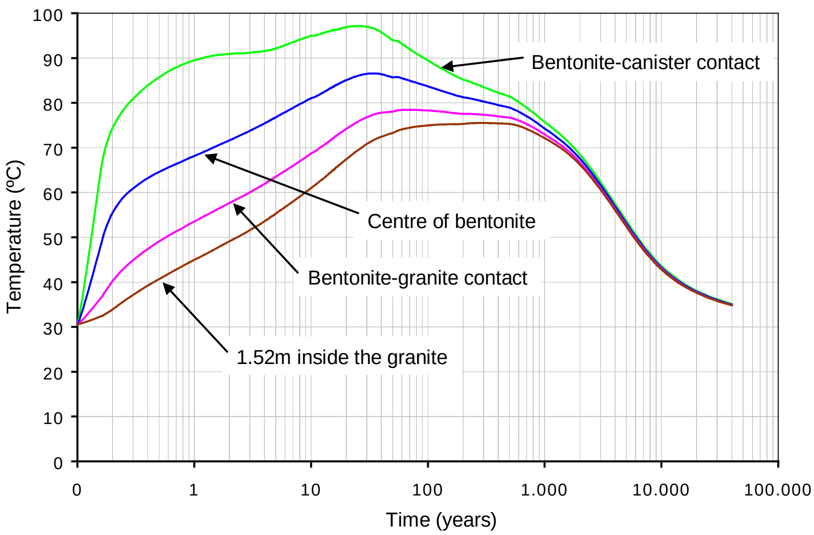

Figure 4– Temperature at different locations in bentonite and granite (Enresa).

The analysis of the repository evolution must be done for each of the scenarios identified in the “scenario selection” process, usually the reference (or normal evolution) scenario and several altered evolution scenarios. It has been found useful to analyse first the evolution of the repository in the reference scenario, and then treat the altered scenarios relying strongly on the models developed and the results obtained in the reference scenario. The evolution of the disposal system done by Enresa isfocused on the post closure evolution of the repository, although those aspects of the excavation and operation phases that could have an effect on the long term repository behaviour are considered too (oxidation of the formation close to excavations, stray materials, etc).

3. Site specific analyses of the repository evolution: development of site specific FEPs from observations

The analysis of the repository evolution relies upon direct observations/study of THMC processes from research zone or site, including if the case an underground laboratory. The description of thermal, hydrogeological, mechanical and (bio)chemical processes results from observations or measures on site from a large program of investigation or underground research facilities. Site specific FEPs are obtained, and then compared to international database for completeness (Andra, SCK.CEN, ONDRAF/NIRAS and Posiva).

Andra: The feasibility assessment for the Meuse/Haute-Marne site was built upon a number of key elements that include the Phenomenological Analysis of Repository Situations (PARS) and detailed, coupled process modelling providing a good scientific understanding based on scientific studies from surface and underground laboratories. To analyse the evolution of the repository (from initial state up to 1 million years), Andra adopted segmentation into "situations"[3] of the repository evolution in time and space. This work is based on a breakdown of the repository into situations, with each of these situations corresponding to a space and time interval within which a few major phenomena dominate the evolution of the components (Figure 12). In this evolution, each state of the repository depends on the former state.

The methodological approach to define the timescales of those situations relied upon spatial fractioning according to the main repository components. Then, segmentation into "situations" corresponds to the phenomenological state of this component as part of the repository or of its environment during a given period of time.

This analysis is based on a detailed description of the aforementioned components. Thermal, hydraulic, mechanical, chemical and radiological phenomena are recorded in this context. It identifies the major THMCR-G processes and determines the uncertainties associated with them. The different thermal, hydraulic, mechanical, chemical and radiological phenomena have their own time characteristics (constants), which determine the successive, distinctive states of the facility. It is possible therefore to define a "typical sequence" of situations by distinguishing between them (Figure 13).

The peculiarity of the « Dossier 2005 Argile » is that it is based on the observations and the results from experiments carried out on a specific clay formation, the Callovo-Oxfordian. The analysis of repository evolution has taken into account the results of the field program (since 1994) and the experiments carried out in the Meuse-Haute-Marne laboratory, and presently continuing. Synthesis of the knowledge has been developed from a set of up streams documents which describe the repository evolution and manage the uncertainties:

- Knowledge reference documents: They provide a complete view of the scientific understanding and describe the state of knowledge, correlatively identify the lack of knowledge and thus contribute in determining the sources of uncertainty and orienting the actions to reduce them.
- The phenomenological Analysis of Repository Situations (PARS). Once a good level of knowledge is reached on each component and the global architecture is defined, the evolution of the repository over space and time is described as finely as possible: this is the purpose of PARS, which describes the phenomena (thermal, mechanical,

[3] The basic Safety Rules, RFS III.2.f, require safety to be quantitatively evaluated by the means of "situations" and so as to avoid confusion with PARS, Andra used the word "scenario" that encompasses all possible evolutions of the repository and that are judged as the most unfavourable in terms of consequences, among all possible evolutions that can be reasonably foreseen.

hydraulic, chemical, radiological) and their coupling throughout the repository evolution and specifies the phases of this evolution from its construction up to 1 million years. The systematic work accomplished with PARS led to a list of uncertainties (on phenomenology, models, data, component characteristics...).

- The conceptual models: These conceptual models reflect the best available knowledge related with each model, providing a picture of the phenomenology that can be applied in safety calculations (see Chapter 11 on modelling strategy). They are described in about forty specific notes, based on the geological and engineered components and the major processes identified in the PARS.

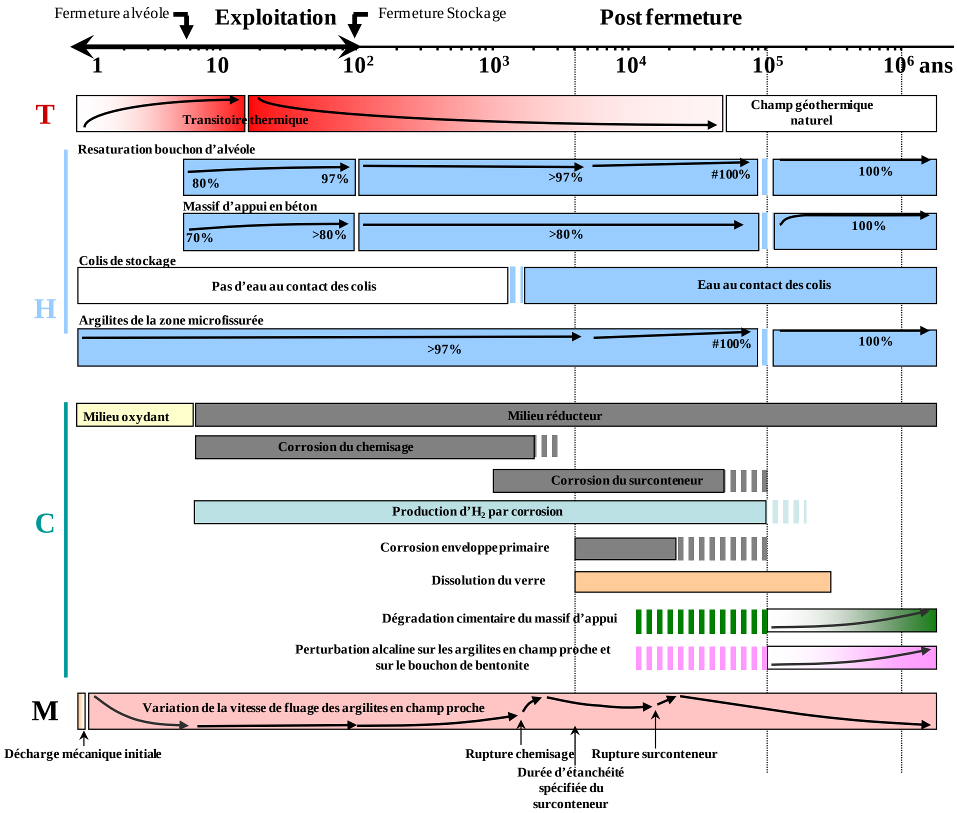

Figure 12 – High level long lived (C) Waste Modules – Chronological evolution of the THMCR processes during the post closure period (Andra).

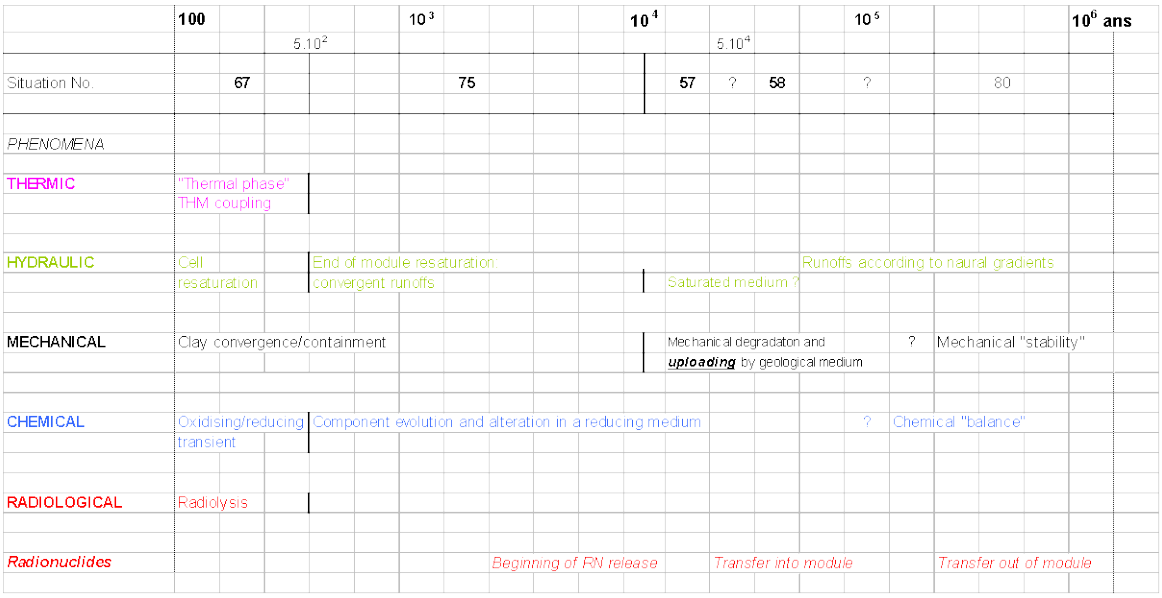

Figure 13 – High level long lived C Waste Modules – Segmentation into situations of the THMCR processes during the post-closure period (Andra).

Posiva: Posiva's methodology for scenario formulation is to follow a top-down approach, i.e., start from the regulatory safety requirements concerning scenario analysis in YVL 8.4 [STUK, 2001] and then consider how FEPs and associated uncertainties affect the various safety functions of the disposal system and their evolution over time. The evolution/s of the repository system partly depend/s on the evolution of the environment at the site or external conditions to which climate change is the main driver.

The evolution of the disposal system will be affected by the FEPs external to the system, and, in particular, evolving climatic conditions at the site. Climatic conditions affect the likelihood of events including major earthquakes that could affect the engineered structures of the repository (such earthquakes are unlikely before the end of the next ice age). Climatic evolution is uncertain due, for example, to the uncertain effects of anthropogenic emissions, and a number of possible climatic scenarios must be considered to take account of such uncertainties. Climatic scenarios are therefore formulated to provide a framework within which the internal evolution of the disposal system can be described. Having defined the climatic evolution scenarios, the scenarios for the evolution of the disposal system itself are formulated. These describe how mechanical, thermal, hydrological and chemical process and interactions identified in the Process Reports affect the evolution of the disposal system and its safety functions over time [Posiva, 2008]. In the description, the thermal, hydrological, mechanical, and (bio) chemical processes that can affect each of the system components (spent fuel, canister, buffer, backfill, and geosphere) have been taken into account.

The expected evolution of a spent nuclear fuel repository at Olkiluoto has been described in three phases (see Figure 14). The time frames considered for both, the evolution of the repository and the site, are according to the Weichselian-R or the Emissions-M climate scenarios. These climate scenarios are defined according to external features, events, and processes (FEPs). The evolution report describes the normal evolution of the **main (base) scenario** (intact canister) under the two climate scenarios. The description of the **main variant** (I: defective canister – no penetrating defect and II: defective canister – penetrating defect) is also included in the evolution report.

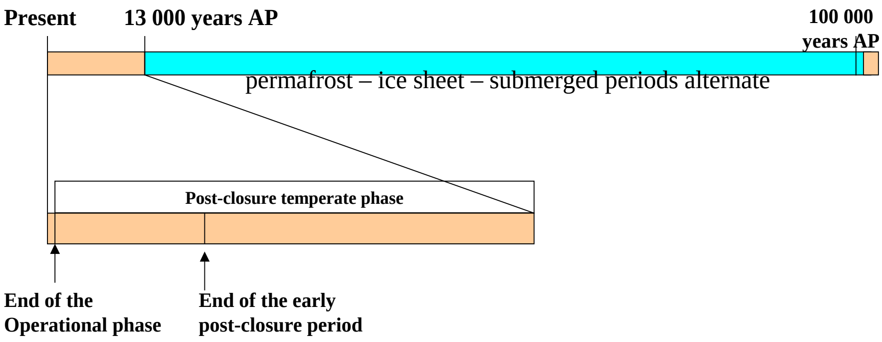

Figure 14 – Scenarios and time frames considered for the safety case (Posiva).

SCK.CEN, ONDRAF/NIRAS: In SAFIR 2 [ONDRAF, 2000], the approach used to identify the possible evolutions of the repository was based on the combination of FEPs into a series of scenarios. The characteristics of the disposal which contribute to safety were first described. These ones fall into three categories:

- The features of the disposal system (the chosen site, the conditioned waste that is being disposed of, the engineered and natural barriers, the different phases in the development and implementation of the disposal etc.);
- The anticipated contribution made by all of these features and their interactions to the level of safety, and the way in which the various components of the safety system function, i.e. their contribution to achieving the safety functions;
- The manner of execution of the construction, operation, closure and controls.

A key element of safety assessment was the identification, analysis and conceptualization of the safety-relevant features, events and processes (the FEPs), e.g. by means of site characterization, general knowledge of the underlying mechanisms of the considered processes, identification and development of suitable models and gathering the required data from tests, experiments and scientific literature. This assessment capability resulted in a catalogue of all relevant FEPs for the deep disposal into the Boom clay. This catalogue was checked and complemented with FEPs from international extensive lists.

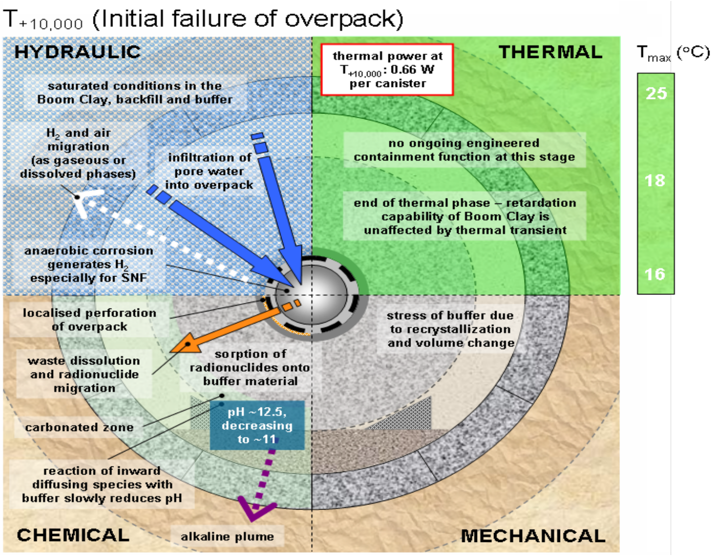

Figure 4. -Transverse cross section through the disposal tunnel showing key processes occurring approximately 10,000 years after emplacement

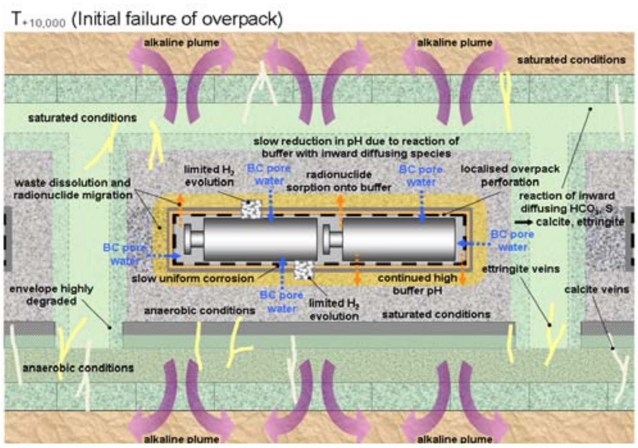

Figure 5 - Longitudinal cross section through the disposal tunnel showing key processes occurring approximately 10,000 years after emplacement

Figure 15 – Story boards representing the transverse and longitudinal cross section of a disposal tunnel (ONDRAF/NIRAS).

One goal of the R&D activities established in the framework of the SFC1 preparation is to reach a better understanding of the phenomenological evolution of the repository system. An example of this deeper understanding has been provided recently with the study of the expected evolution of the Engineered Barrier System (EBS). In order to structure the analysis of the plethora of processes taking place, the expected evolution of the EBS has been divided in key time sequences and in classes of processes (thermal, mechanical, hydraulic and chemical). Each time sequence corresponds to a state of the repository characterized by key processes and events. Notable differences are expected in the extent of certain processes, depending on whether the supercontainer contains HLW or spent fuel. The expected evolution of the EBS focuses on processes and events within a single disposal tunnel. The timescale is normalized to closure of the tunnel after a ten year operating period at T0, however the processes are considered as soon as the excavation of the repository.

The successive stages in the evolution are illustrated by a series of diagrams, called "storyboard" representing the transverse and longitudinal cross section of a disposal tunnel (Figure 15). These storyboards aim at illustrating the processes taking place concurrently. They will be used as basis for a further study of the THMC coupled processes in SFC1 in complement to the findings of the experiment PRACLAY which is currently in progress.

7.7 Lessons learned and on going planned projects

7.7.1 Regulators

GRS-K: GRS has drafted a report with suggestions for so called "Safety Requirements" [Baltes, 2007] which includes revised and additional requirements to all the addressed technical areas. Furthermore it describes in a more specified way how the evolution of the repository system has to be analysed and what has to be taken into account. The implementer has to describe and to assess the potential evolutions, due to internal and external causes, of the geological barrier system and its safety functions in the frame of a geo-scientific long-term prognosis.

IRSN: IRSN performs its own studies to improve its knowledge and understanding of the processes occurring during the period of a repository system. Those studies concern the main topics related to the evolution of the repository system. Most of them are performed within European project focussed on specific aspects of the repository like NF-PRO or MICADO projects.

7.7.2 Developers

Lessons learned and ongoing planned projects are very specific to the organisation, depending in particular on the progress of their project, their regulations, and if the case, review of safety cases. In an iterative process, the exposed methodology will be adapted, developed, or sometime reconsidered like SCK.CEN-ONDRAF/NIRAS who is developing a new methodology for future safety cases.

Andra: The innovative approach called phenomenological analysis of repository situations (PARS) divides the repository into segments of time and space to give a set of situations that are easier to understand and control, making it possible to transcribe the knowledge acquired into usable material. It provided a robust understanding of the repository's life history (from the initial state up to 1 million years), a general description of it and the main phenomena involved. In close connection with the modelling strategy, such an approach will be reconducted for future safety cases, taking into account sound experimental, scientific and characterisation programs on the Meuse/Haute-Marne site. Transient phases, together with the operational phase will be detailed.

Enresa: Since the canisters ensure total containment during the initial thermo-hydro-mechanical transient phase, the detailed description of this transient phase is not critical. What needs to be known with reasonable precision is the state of the bentonite when the thermal transient has passed and canisters start to fail. It is crucial to be confident that the safety relevant properties of the barriers are available when the transient phase finishes and beyond. Enresa is making developments on this topicand is involved in different international projects that study different topics relevant for the evolution of the disposal system. For instance, in FUNMIG project the effects of the carbon steel corrosion products and concrete degradation products on bentonite and natural clays were studied.

GRS-B: Considering the requirements of the new German “Safety Criteria” rock salt is still a favourable option for waste disposal in deep geological formations. In the past, a lot of arguments have been collected for this option. The outcome of the compilation of relevant FEPs in a FEP-list for spent fuel and HLW for a reference site of a salt dome in Northern Germany supports this conclusion. For the compilation of this list a combination of elements of the top-down and the bottom-up approach was used. This turned out to be a useful approach to gain a complete list of relevant FEPs for the evolution of the repository system. The crucial point in this approach is to create a comprehensive and comprehensible record of all decisions made during the compilation of the FEP-list. The traceability of these decisions is an essential part for the definition of a set of scenarios that encompass all relevant possible future states of the disposal system (i.e. the definition of a normal evolution scenario plus several altered evolution scenarios).

NDA: This process of FEP analysis demonstrated the importance of being able to communicate safety case results in a way that demonstrates understanding of the initial state and evolution of the repository system.

NRG: Usage of the FEP catalogue leads to more transparency. However, an enormous amount of expert judgement is needed to evaluate all FEPs for all scenarios and subsystems, including estimations and predictions of future circumstances. Various future changes, especially climatic changes and their consequences, are difficult to predict, but may highly affect the biosphere conditions and therefore dose conversion factors. It is expected that the PROSA procedure for identifying scenarios will be extended by the application of ‘safety functions’ for future safety studies. It is also expected that it will be very useful to present the results of PA-calculations along the lines of safety functions. At present there is no ongoing work in the Netherlands on the topic of the evolution of the repository system. Research on climatic changes is however a main topic.

NRI, RAWRA: It turned out that using interaction matrices can make some interactions between system components more visible and will help not to forget some important issues, but this approach is difficult to formalise and relate directly to the main objective of the system. It is also very difficult to estimate the importance of some interactions. All the identified interactions will be specified and transformed into indirect safety functions with some tentative, quantitative requirements. Further experimental and modelling work is needed to determine the evolution of repository barriers. This work will be based on the results achieved in international or national projects of other countries.

Posiva: Currently, the expected evolution of the repository system does not give place to consequence analyses (radionuclide transport analyses). The analyses performed were related to the long-term performance of the engineered and natural barrier system. The multibarrier system hindered the release of dispose radioactive substance into the host rock and hence into the biosphere for several tens of thousands of years which is in accordance with Section 8 of the Government Decision.

Other lines of evolution, where radionuclide release is considered, have not been described in detail, but assessment scenarios are set that give place to consequence analyses. Posiva has implemented the approach to the Safety Case Posiva 2008. In the new approach the analysis and description of scenarios and the consequence analyses is to be integrated in one or at most two different reports. It is to note that the analysis of the scenarios include the evolution of the repository and the site altogether with the consequence analysis for safety assessment as part of the update of the approach to the Safety Case. Although the effects of external FEPs are already integrated in the current approach, it is intended to add transparency and traceability to the safety case and the relationships between the core of safety assessment and the related documents.

SCK.CEN, ONDRAF/NIRAS: The understanding of the evolution of the repository system in SAFIR 2 was based on a three decades R&D programme. Through this programme, key-phenomena governing the evolution of the repository, and potentially affect it, have been well identified and a good basis of understanding has been provided. In the framework of the further development of the assessment basis for the SFC1 particular attention is given to the refinement of specific processes: a study of the expected evolution of the EBS is ongoing which includes the investigation of detailed processes such as the corrosion processes. Concerning the far field aspects, deeper studies of the chemical interactions between the radionuclides and the clay and the organic matter are carried out currently. The story board will be used as basis for a further study of the THMC coupled processes in SFC1 in complement to the findings of the experiment PRACLAY which is currently in progress. This experiment is designed to demonstrate at full scale (except for the length of the disposal gallery) the technical feasibility of the deep disposal of high-level heat-emitting waste in the Boom Clay. The thermo-hydro-mechanical behaviour of the clay, the lining, the backfill material and the disposal tube when exposed to a significant increase in temperature (80 to 120°C) is studied.

7.8 Conclusions

The participating organisations defined the Analysis of repository evolution as:

- Identification and study of processes (THMCR-G) effects and influences of waste and repository induced phenomena, of the site, of external events or features (natural phenomena, or human induced phenomena)
- Predictions/modelling of potential evolutions of site and repository (link with modelling topic) including influences of any disturbances (natural or human induced).

All organisations acknowledge that the safety analysis relies upon a thorough knowledge and understanding of processes and phenomena likely to evolve in the repository, on the long term behaviour of the repository and its environment. In that respect, most of them indicate a strong link between the analyses of the repository evolution and the scenario development in their strategy. Moreover, it can be a key element for the overall safety strategy that can be used together with the safety functions in order to derive scenarios, evaluate the performance of safety function and inform design studies.

Analysis of the repository evolution collects, analyse and organise the FEPs with the aim at obtaining the relevant FEPs to consider in scenarios and their associated uncertainties: which FEPs or THMCR-G processes can affect a component, a barrier, or a safety function? How do FEPS and THMCR-G processes affect the evolution of the disposal system? Uncertainties and scenarios are derived from the analysis of the repository evolution.

Requirements from authorities provide guidance that implementers have to conform to. Regulators may also have specific requirements and statements that have a direct impact on the assessment of the evolution of a repository system (GRS-K, GRS-B, IRSN, Andra, and Posiva), although the German regulations currently undergo a thorough revision (GRS-K), in particular:

- To justify (or show) a good understanding of the processes having influences on the evolution of the repository system (Andra - IRSN),
- To identify (and model) the spectrum of potential evolutions of the disposal system (expected evolution or alternative evolutions resulting from internal or external FEPs (endogenous and exogenous) including human actions (GRS-K in preparation, Posiva, and Andra).
- To take account for a series of FEPs in scenarios. Scenarios should consider features, events and processes which are potentially significant to long term safety. In some cases, possible evolutions of the repository system have to be distinguished according to their probability, as the probability defines the way how to deal with an evolution of the repository system and its consequences (GRS-K and GRS-B). Probability of events may have to be considered (Andra, IRSN).
- Give recommendations on timeframes to be considered (GRS-K, IRSN, Andra, Posiva).
- To assess the performance of safety function.
- To account for specific methods such as to assess the occurrence probability of relevant factors playing an important role (GRS-K).

Some organisations have no specific regulatory requirements or guidelines regarding how to analyse the evolution of the repository system (Enresa, NRG). Some indicate the necessity of evaluating the repository evolution but without specific guidelines on how to do it (NRI). Regulations are in preparation (SCK.CEN, ONDRAF/NIRAS, NDA).

Due to regulation and due to the maturity of the project, the place given to this analysis may vary depending on the overall strategy adopted by implementers (e.g. top-down or bottom up approach, or a mix of both):

- Analyses of the repository evolution are used to derive uncertainties and scenarios. The objective is to obtain the relevant FEPs to consider (NRI, Posiva, SCK.CEN, ONDRAF/NIRAS, NRG, and NDA, Andra).

- Analysis of the repository evolution is a key component of the safety case, not only for scenario development (Enresa, Andra, and NRG)
- Analysis of the repository evolution is studied in connection with the safety function via the use of safety statements: which effects (THMC - geochemistry) can affect the functions (SCK/CEN, Andra), see topic dedicated on "safety strategy" for both organisations.
- Analysis of the repository evolution can be a support to proof safe enclosure as in the case of GRS-B.

Analysis of the evolution of the repository system is the background for safety analyses:

- It aims at identification, analysis and conceptualization of FEPs and their associated uncertainties. The objective is to obtain the relevant FEPs to consider, to analyse them (which include to define the associated analyses), and to organise them and derive conceptual model (usually with according to time and space).
- It is a background for definition and assessment of scenarios. It is the basis for scenario development (reference or altered one). It can be a basis for uncertainty analyses (qualitative safety analyses or quantitative). It aims at identifying which THMCR-G effects or FEPs can affect the safety functions, or the "barrier" and how those FEPs and their associated uncertainties can affect the evolution of the disposal system.
- It also aims at identifying performance of safety functions.
- It can provide information for design studies. For instance, it can describe the evolution with time of the material being used. Design architecture may also be a base for analysis of the repository evolution (breakdown into space representative of specific components or barrier).

To achieve these goals, main approaches described by the different organisations are:

- Identification and classification of FEPs using a structured analysis of FEPs from international databases - The analysis of the repository evolution relies upon a structured FEP analysis which uses national/international FEPs databases. Analyses of the evolution rely upon identification and analyses of relevant FEPs in order to derive scenarios (GRS-B, NDA, NRI, NRG). Classification may define Super FEPs as for example in the probabilistic approach of PROSA (NRG).
- Well supported detailed modelling: creation of conceptual models based on analysis of FEPs. This is the approach followed by Enresa. Based on international database, some scenario cases are defined. Then conceptual model are created based on analysis of FEPs within a scenario. Expert judgement and FEP list from international database allow identifying all the relevant processes to be considered in a detailed modelling of the repository evolution.
- Phenomenological analyses of the repository evolution: development of site and/or concept specific FEPs from observations and data acquisition (Posiva). The approach describes and identifies the possible evolution of the repository using a sound scientific knowledge of THMCR-G processes for a particular rock formation. The analysis of the repository evolution relies upon direct observations/study of those processes from

research zone or site, including if the case an underground laboratory, (Andra, SCK.CEN, ONDRAF/NIRAS and Posiva). The description of thermal, hydrogeological, mechanical, Gas generation and (bio)chemical processes results from observations or measures on site from a large program of investigation or underground research facilities. Site specific FEPs are obtained, and then compared to international databases for completeness (Andra, SCK.CEN, ONDRAF/NIRAS and Posiva). They are used to derive scenario (using safety functions).

As a general feature, the approaches:

- Consider the identification and analyses of (Chemical (C), Thermal (T); Hydraulic (H); Mechanical (M); Gas formation (G); Radiation (R)) induced processes and the study of their interactions between major disposal systems components.
- Consider internal repository induced processes, and external events such as glaciations, and human induced phenomena.
- The description of the THMCR-G processes and their evolution in specific timeframes. Those one may be defined by regulation but they can also be linked to specific FEPs to take into account such as climatic and geologic evolution (Posiva). Timeframes are also defined according to specific THMC processes such as thermal phases (Andra, SCK.CEN, and ONDRAF/NIRAS) or coupling of all the THMC processes (Andra, Enresa).
- The evolution of near and far field components and the evolution of the biosphere are usually described. They can be analysed separately to account for specific FEPs (that may affect only the far field for instance), or in a more integrated approach in order to obtain a phenomenological evolution of specific components of the repository system, in particular those contributing to safety functions.

Some divergences may appear due to:

- Progress in the project, in particular if a potential site or rock type is defined, or note for example,
- Regulations which may request specific FEPs to be accounted for (such as potential climatic changes), or specific methods to be applied (probabilistic approach to assess the occurrence probability of relevant factors playing an important role, for example).

The development of the project is for most organisations a stepwise process. The maturity of the project and particularly of the site investigation (including site localisation processes) influences the approach used or developed by the organisations in order to analyse the evolution of the repository. Some examples show that if the project is generic or at an early stage in the processthe FEPs to consider in the analysis of the repository evolution rely upon international database. When a site or a possible area of implantation in a rock formation has been selected, the organisations develop site specific FEPs and concept specific FEPs associated to more and more phenomenological representation of the system.

From the contributions, analyses of repository evolution evolve from generic approach to more and more “phenomenological approach”. Together with the progress of the project, and the successive iteration of the safety case, more and more realistic analyses of repository evolutions are achieved. They are usually strongly linked with sound experimental and characterisation programs on real site. Recent developments illustrate such phenomenological approach and breakdown the FEPS into time and space. Timeframes are defined according to the duration of some major processes (as thermal phase), and they may be used for detailed description of all the processes in those defined time frames. Andra developed the Phenomenological Analysis of Repository Situations (PARS) and ONDRAF/NIRAS developed the so-called “Story Boards”.

Transient phases are explored; some couplings of processes and/or phenomena are mentioned by Andra, Enresa, NRI and ONDRAF. Such couplings are still in development but some examples of HM, TH, THM, and G are given in some contributions.

From the lessons learned and perspective, most of the organisations will continue to use their methods with some developments and adaptations according to the evolution of their project (Andra). It can be outlined that regulations just have been revised (IRSN), or are under revision (GRS-K) or preparation (ONDRAF/NIRAS). Others like SCK.CEN-ONDRAF/NIRAS, and in some way Posiva, are reconsidering their approaches and methods for future safety cases. Some EWG organizations (regulators), such as IRSN are being developing its own approach and participate in European projects. Enresa is involved in international projects that study different topics relevant for the evolution of the disposal system.

Since some national project became more mature, the need for descriptive understanding of the repository system evolution with their associated uncertainties appeared. Examples are phenomenological representation of THMCRG processes (site and concept specific FEPs) or external FEPs in time sequences and space can be found in several safety cases. These descriptive understanding of the disposal system became, together with the use of functional analysis, the basis for derivation of scenarios.

7.9 References

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8. Definition and assessment of scenarios

8.1 Background/ Introduction

One of the first steps towards safety assessment is the identification of all relevant factors in terms of the long-term safety of the repository as well as their combination to develop scenarios. A systematic and transparent way for this work is vital in order to demonstrate compliance with regulations and to increase the confidence that all essential factors have been taken into account [NEA, 2001].

Most of the participating organisations have a lot of experience with systematic scenario development due to the former and / or current application of own, modified or adapted methodologies in safety assessments. Previous international projects have also increased knowledge and experience amongst participants. In the following are some examples that underline the detailed work in the field of scenario development by different organisations:

- << Definition and assessment of scenarios were carried out in the Performance Assessment (PA) of HLW repositories in granite and clay. >> [Enresa]
- << Definition of scenarios is being dealt within the Process report [Posiva, 2007] scheduled by the end of 2007. >> [Posiva]
- << Definition, scenario development and assessment of scenarios were carried out in the Safety Evaluation of HA and MAVL repositories in clay (Dossier 2005) >> [Andra].
- << Systematic scenario development in Czech geological disposal programme started in 1996 by analysing broad approaches, primarily Sandia Scenario Selection Procedure and SKI/SKB scenario development approach. The scenario development in Czech programme in further years was affected by participation of Czech specialists in Performance Assessment Advisory Group (PAAG) of the Radioactive Waste Management Committee (RWMC) of NEA and by consequent NEA publications. >> [NRI, RAWRA]
- <<Nirex (now part of the NDA) undertook extensive identification and development of scenarios for an ILW repository concept, with a series of reports published and reviewed by the OECD-NEA in 1999.>> [NDA]
- << For scenario development three main phases can be distinguished in the Belgian radioactive high-level waste (HLW) disposal programme:
  - phase 1 (period 1978 - 1990): a number of less systematic approaches were applied; these approaches will not be discussed in the present paper;
  - phase 2 (period 1992 - 1999): a systematic approach based on a catalogue of features, events and processes (FEPs) was introduced; this approach was used in the SAFIR 2 (safety and feasibility interim report) report [ONDRAF/NIRAS, 2001];
  - phase 3 (period 2004 - 2012): the new approach is still in development, partially within PAMINA, and will be applied for the Safety and Feasibility Case 1 (SFC 1). >> [SCK/CEN, ONDRAF/NIRAS]

- << In the late 1980's the VEOS study (Safety evaluation of disposal concepts in rock salt) has been performed in the Netherlands. VEOS used a scenario approach followed by a deterministic consequence analysis and several deterministic sensitivity studies. In the early 1990's a generic probabilistic safety analysis (PROSA) of the Dutch generic reference disposal concept has been performed. In this study a systematic approach to scenario selection has been used that ultimately leads to a set of selected scenarios that covers all aspects relevant for the long term safety. >> [NRG]

The term scenario development is used to describe the compilation and arrangement of both scientific and technical information as a fundamental basis for the assessment of long-term safety for a radioactive waste repository. This includes the identification of relevant FEPs, the modelling of the scientific basis, and the derivation of calculation cases. Therefore scenario development constitutes the overall framework for the discussion of the evolution of the repository, calculation cases and their results, as well as failures or weakness of models, attributed to unknown or less known mechanisms [NEA, 2001].

In the following are some selected statements from the contributions that reflect in principle the mentioned context, role, and essential elements of scenario development and the common opinion of the participants.

Context of scenario development in the frame of safety assessments:

<< Scenario development is a key topic in the frame of the safety analysis, since it has an important role in capturing uncertainties and quantifying their influence, in verifying fulfilment of safety functions associated with disposal components, and in quantifying the dosimetric impact due to the disposal system. >> [IRSN]

<< Safety assessments for radioactive waste repositories in deep geological formations are an integral part of the comprehensive demonstration of the safety of the repository in the post-closure phase. The demonstration will be conducted on a site specific basis in consideration of the geological, geochemical, and geotechnical state of the repository system, and its long-term predictions as well. The safety assessment includes the scenario development, consequence analysis with uncertainty and sensitivity analyses, and the demonstration of the compliance of prescribed protection objectives. >> [GRS-K]

Role of scenario development:

<< The need for carrying out a scenario development in safety assessment of radioactive waste disposal facilities arises from the fact that it is virtually impossible to predict exactly what will be the evolution of the disposal system through time.

A scenario describes one possible future of the disposal system, corresponding to a combination of events and processes together with their characteristics and their chronological sequence. The expression scenario development is used both for the identification of the set of scenarios that will be representative of the different states of the disposal facility and for the identification, general description and selection of the possible safety-relevant features of the disposal system for one defined disposal evolution. >> [AVN]

Consideration of the evolution of the repository as an essential element:

<< The possible evolution of a repository system can be addressed in terms of a base scenario that provides a broad and reasonable representation of the natural evolution of the system and its surrounding environment, and a number of variant scenarios that represent the effects of probabilistic events. >> [NDA]

<< "Scenarios" are simplified descriptions of the repository. The system representation for the safety model thus developed is based on a "Normal evolution scenario" (SEN), which purpose is to provide a bounding value for all likely or probable future evolutions. Beside that, some altered evolution scenarios (SEAs) were defined in principle. >> [Andra]

<< By a stepwise process, the scenario development aims at choosing a limited number of different scenarios that, taken together, illustrate the behaviour of the system and its safety and improve the understanding of mechanism of the system by testing the reactions of the system under certain stresses. In other words, a relevant strategy of scenarios should allow defining all the situations to be considered and should allow classifying them by their occurrence in order to structure the performance assessment and the safety case by identifying the need for further work to avoid, mitigate or reduce uncertainties and to evaluate their effect. >> [IRSN]

Common Opinion:

A consensus was reached among the participating organisations regarding the key role of scenario development in safety assessments. In this context, scenario development constitutes the fundamental basis for consequence analysis. The scenario development has to indicate in a reasonable manner that all relevant FEPs have been taken into account. Furthermore, compliance with the appropriate regulations has to be shown.

8.2 Regulations and Guidelines:

Regulations and guidelines are, in general, a worthwhile basis for both the developer and the evaluator. The developer benefits from guidance which indicates how the compliance with provided requirements could be demonstrated. The evaluator can draw on a framework given by regulations that facilitates the review work, assessments etc. of relevant documents in the licensing procedure.

Therefore regulations should not only include requirements that have to be fulfilled by the developer but also acknowledge inevitable uncertainty about future developments. Moreover it should offer guidance in areas where there is great uncertainty about the future that makes uncertainty management difficult, for example in consideration of the biosphere and human activities.

In principle, international guidance is addressed in the respective legal national frameworks. The international guidance does not consider scenario development explicitly. However, it constitutes an initial basis for the elaboration of specified rules or guidelines with regard to the handling of scenarios. Actually, only two countries Finland and France have implemented specific regulations or guidelines concerning the handling of scenarios. Whereas the existing Basic Safety Rule RFS III.2.f from 1991 in France is currently revised. Some essential aspects of the regulations are shown in the following:

<< According to STUK's regulatory guide, scenario analysis shall cover both the expected evolutions of the disposal system and unlikely disruptive events affecting long-term safety. The scenarios shall be composed systematically from features, events and processes, which are potentially significant to long-term safety and may arise from

- mechanical, thermal, hydrological and chemical processes and interactions occurring inside the disposal system
- external events and processes, such as climate changes, geological processes and human actions. >> [Posiva]

<< Basic Safety Rule RFS III.2.f. recommends that in the framework of a safety analysis, should be considered :

- A reference situation (i.e. normal evolution scenario), considering the foreseeable evolution of the repository covering situations considered certain or highly probable.
- Hypothetical situations (i.e. altered evolution scenarios) covering uncertain events.
- The event recommended in the Basic Safety Rules RFS III.2.f. for considering the effects, are the following situations:
- Major climatic changes (including changes due to human activity, greenhouse effect)
- Exceptional vertical movements or earthquakes.
- Various possible forms of human intrusion
- Geological barrier defects.
- Waste package defects.
- Engineered barrier defects (seal defects). >> [Andra]

<< Implementer develops its own set of evolution scenarios taking into account the potential evolutions of the disposal system and their related uncertainties in agreement with the RFS III.2.f. However, regulators can recommend including specific situations in the development of the scenarios or integrating technological uncertainties in the normal evolution scenario.

- The post-closure safety assessment must cover the assessment of the future behaviour of the repository and checking that individual exposure is acceptable. The approach adopted shall consist in considering a limited number of situations representatives of the different families of events or sequences of events such that the associated consequences are the greatest among those of the situations of the same family. The families of events or sequences of events adopted shall be those considered to be conceivable among all those which are a priori possible.

- The events and processes constituting the situations adopted for the purposes of the safety analysis must be modelled and characterized. This characterisation shall be essentially iterative insofar, in particular, as the determination of situations considered is liable to be refined on the basis of a better understanding of the barriers and their behaviour. >> [IRSN]

Regulations in a more general sense were formulated by Czech Republic and UK which include the following:

- << Legislative regulation supposes that performance assessment evaluators will describe behaviour of the system and its components and determine under all possible sets of events and processes which occur in the future, under all possible scenarios. Development of scenarios is thus an implicit requirement of legislation, but with no exact guide.
- It has been defined by regulations of Czech regulatory body (State Office for Nuclear Safety) that the potential individual dose raised by repository existence, has not to exceed 0.25 mSv/yr for normal evolution scenarios and/or 1 mSv/yr for emergency scenarios. There exists no other quantitative limitation postulated by nuclear legislation or some other concerning scenarios. >> [NRI, RAWRA]
- << UK regulatory guidance specifies that: “After control is withdrawn, the assessed radiological risk from the facility to a representative member of the potentially exposed group at greatest risk should be consistent with a risk target of 10^{-6} yr^{-1} (i.e. 1 in a million per year).” This specification includes all situations (scenarios) that could give exposure: “Radiological risk to a representative member of a potentially exposed group is the product of the probability that a given dose will be received and the probability that the dose will result in a serious health effect, summed over all situations that could give rise to exposure to the group.”>> [NDA]

Belgium is developing general regulations on radioactive waste disposal while Germany, is currently preparing detailed regulations for scenario development. Listed below are some examples of intended specific regulations:

- << In Belgium, it is up to the operator to define for each project of disposal a relevant list of scenarios adapted to the considered case. The aim is to establish a limited (e.g. ten or so) but relevant list of scenarios that correctly enables to appraise the possible extent of the evolution of the system along time until the very-long term, from the scenarios the most “realistic” up to the scenarios the most “pessimistic” (and less likely), also taking into account possible disruptive events.
- The strategy followed by the operator for the scenario selection should be clearly explained in the Safety Case.
- The list of scenarios should then be discussed with the regulator, and eventually approved by him.

- With such a position taken by the nuclear safety authority, the necessity for the operator to clearly justify the reasons for the choice of the selected scenarios is crucial.
- It is not the intention to impose a particular methodology to the operator for developing the scenarios.
- The regulatory approach concerning scenario development should consider, on the one hand, the different categories of scenarios which need to be developed and, on the other hand, how to appraise them. >> [AVN]
- << The long-term safety analysis has to comprise, the scenario development and the consequence analysis for the proof of compliance of protection objectives. The consequence analysis must underlie scenarios obtained from the scenario development. Strategy and methodology of the analyses have to be shown.
- It is to carry out a scenario development for the repository system. Here the potential evolutions of the repository system according to scientific findings, which are caused by endogenous and exogenous processes, have to be considered. Furthermore, the relevant scenarios for the safety case, with the exception of human intrusion, have to be identified.
- The scenario development has to be documented in a transparent and comprehensible manner. Each individual step has to be justified, and relevant decisions have to be explained clearly.
- Scenarios have to be assigned into the scenario classes "Likely scenarios", "Less likely scenarios", and "Scenarios that need not to be considered any further". This classification has to be justified.
- There are no requirements regarding the choice or use of a certain method, procedure and approach for the development of scenarios. It is left to the implementer to decide which tools, programmes or instruments are useful or not for the task of scenario development. >> [GRS-K]

<< There are presently no regulatory requirements and provisions of the remaining countries, Netherlands and Spain, which directly relate to the definition and assessment of scenarios. >> [NRG], [Enresa]

The following conclusion to the issue "Regulations and guidance" by the participants, take into account the compiled facts from above and the findings from the workshop:

There are different states regarding regulations in terms of scenario development of the participating organisations and countries respectively. Some countries have established regulations, others are currently developing specific regulations or revising existing ones, and others in turn do not have any specific regulations concerning scenario development at all. Therefore, no consensus exist whether regulations are needed or not from the view of developers. For some participants, guidance in general and regulations in terms of human intrusion and the biosphere are seen as helpful instruments. Others in turn, consider guidance and regulations as a necessary basis. Different opinions exist also regarding the question if the regulator should provide a set of scenarios which have to be investigated by the implementer.

8.3 Terminology

Scenario development plays a key role in many technical fields and in particular in safety assessments for radioactive waste repositories across all concerned countries. Given the fact that there are different methodologies, approaches, procedures etc. for addressing scenarios in safety assessments the meaning and also the number of terms and terminologies varies significantly. The use of different terms and additional concepts accompanying the process of scenario development does not actually facilitate the situation and might lead to some confusion. At least, it makes the communication on a national as well as international basis more difficult. In order to aim for a common harmonized terminology, international bodies like IAEA and NEA provide glossaries and definitions of appropriate terms. In this context the following definitions were given:

OECD/NEA (Definition for scenario development) [NEA, 1992]: Scenario development is defined as "the identification, broad description, and selection of potential futures relevant to safety assessments of radioactive waste repositories."

IAEA (Definition for scenario) [IAEA, 2007]: Scenario is defined as "a postulated or assumed set of conditions and/or events. Most commonly used in analysis or assessment to represent possible future conditions and/or events to be modelled, such as possible accidents at a nuclear facility, or the possible future evolution of a repository and its surroundings. A scenario may represent the conditions at a single point in time or a single event, or a time history of conditions and/or events (including processes)."

As indicated above, the definition and use of terminologies is dependent on specific national frameworks and safety case methodologies. This is reflected in the contributions from the participants. The main observations made by the review of these contributions can be summed up as follows:

- Positions and content regarding definition of terms and concepts used differ widely.
- Only a few contributions contain a definition for "scenario development".
- Some deliver no definitions, neither for "scenario development" nor for "scenario".
- Some refer to definitions from other organisations and documentations respectively (IAEA, NEA, WIPP).
- Lots of additional concepts in connection with scenarios and also synonyms were used.

In the following, the different aspects of scenario development with respect to definitions, terminologies, additional concepts, use of synonyms etc. corresponding to the contributions are discussed:

Obsolete terms, new terms and modified definitions:

Formerly the term "scenario analysis" was often used similarly as "scenario development". Some organisations or countries have used "scenario analysis" also for the calculation of consequences with respect to defined scenarios. In the meantime the term "scenario development" has become generally accepted for the derivation and definition of scenarios. Another similar aspect is given by different concepts, which have the same meaning but one or more of them were used in former times, e.g. initial scenario and base scenario, and thus still exist in respective documentations. This situation might not only lead to some confusion but also have to be taken into account for "information preservation" another relevant subject that relates inter alia to "human intrusion". The same applies for introduced new terms such as "safety functions" which might play an essential role for scenario development in future times. It is also conceivable that definitions, e.g. scenario development, be subject of changes in the course of time. This is a natural process in an evolving technical field. Therefore it is essential to be aware of such aspects in order to avoid misinterpretations and to take action with respect to the information and documentation of future generations.

Common approach:

As stated before there are many concepts and synonyms for the term "scenario". It should be noted here that there are possibly no common features concerning the used terms and concepts, e.g. the same term can have different meanings in different nations. However, a common approach exists regarding the general consideration of scenarios which can be divided in principle into two groups. That might help to differentiate the great number of used concepts in a rough manner.

All organisations consider a base case which describes a starting point for scenario development. The participants called this overall case "central scenario" that represents one of the mentioned groups. Provided scenarios that can be assigned to the "central scenario" are normal evolution scenario, base scenario, reference scenario, initial scenario, main scenario and expected evolution scenario.

Remaining scenarios were assigned to the group "other scenarios". To this class belong scenarios like altered evolution scenarios, variant scenarios, disturbance scenarios, disruptive scenarios, scenario representations, representative (umbrella) scenarios, assessment scenarios, additional scenarios, what if scenarios, what if cases, conventional scenarios, situations, human induced scenarios, human intrusion scenarios and stylised scenarios.

Further dividing in groups is presumably feasible e.g. scenarios like representative scenarios which indicate an overall group for similar scenarios, but was not intended and has actually no influence for the conclusion.

Taking into account the above mentioned aspects and the discussion on the workshop, the participants came to the following conclusion:

A wide range of definitions and concepts related to scenario development and scenarios exists. Use and meaning of terms differ significantly from country to country. But all of them have in common, that a central, or reference scenario is considered as a starting position with appropriate additional scenarios. It was stated, that definitions provided by IAEA and OECD/NEA regarding the terms "scenario" and "scenario development" constitute a valuable initial basis which can be modified / adapted according to the respective national conditions.

Another outcome of the discussion was that there is no need to harmonise the terminology across the different countries, but a common understanding is necessary for communication and for avoiding misleading discussions.

8.4 Methodology

The methodology for scenario development provides the procedure for the description, definition, derivation and identification of scenarios which might have an influence on the performance of the repository for the assessment period. Developed scenarios by the methodology build the basis for calculation cases that have to be considered in safety analyses.

Up to now, a number of methodologies and techniques were applied, e.g. directed diagrams, event and fault trees, matrix diagrams, influence diagrams, bottom up approach, top down approach, and judgemental approach [NEA, 1992], [NEA, 2001].

The considered wide range of methodologies can be also confirmed by the different contributions, where the following observations were made:

- << Used approach is mainly deterministic according to regulations >> [Andra]
- << Addressing possible future evolutions of the repository by defining a base scenario and variant scenarios >> [NDA]
- << Approaches based on the Sandia Methodology and on the SKI/SKB scenario development procedure were used >> [Enresa], [NRI, RAWRA].
- << Approaches on the basis of expert judgement were applied >> [NRI, RAWRA].
- << Top down approach was used or currently being formed >> [Posiva], [NRI, RAWRA]
- << Scenario development on the basis of FEP classification taking into account the “barrier state” caused by the FEP (PROSA method) was performed >> [NRG], [SCK/CEN, ONDRAF/NIRAS].
- << Some are planning or taking into account safety functions for scenario development >> [Andra], [SCK/CEN, ONDRAF/NIRAS], [NRG], [NRI, RAWRA], [GRS-K].

It could be also observed, that the detailed approaches of scenario development differ widely but the underlying basic approach is nearly the same in all countries. This more or less common approach comprises the description of a central or reference scenario (terms used for this scenario are normal evolution scenario, base scenario and reference scenario), and the definition of so called alternative developments which are described by scenarios named as altered evolution scenario, variant scenarios, disruptive scenarios etc. (cf. Chapter 8.3).

The procedure itself has also some components which are widely used in the respective methodologies. These components are:

- Collection of FEPs
- Screening of FEPs
- Combination of FEPs to scenarios or grouping of phenomenological situations based on repository evolution towards a normal evolution scenario (in that case, checking of results to FEPs database)
- Grouping of scenarios to representative scenarios

Although this seems a logical sequence of steps to develop scenarios, in practise the process of developing scenarios is iterative. E.g. screening of the FEPs requires some knowledge of the central evolution scenario, and will also depend on identified altered evolution scenarios.

Along the different components the involvement of expert judgement is also a common feature. Additional common features are the use of the international NEA FEP database as a basis for the collection of FEPs which are then screened and / or enhanced by specific FEPs depending from national requirements, repository sites and disposal concepts.

An essential key topic in scenario development is the question of whether the proposed methodology will be able to deliver a complete, comprehensive or sufficient set of relevant scenarios. In this context the application of systematic methodologies for organising the information and the collected FEPs might help to identify gaps and shortfalls and therefore provide more confidence of reasonable or sufficient completeness. A formalised approach for the clear, transparent and accurate documentation of screened FEPs or grouped scenarios might also support the ultimate goal of completeness.

As a result from the observations and the discussion on the workshop the participants summarises the following:

Similarly to the issue "Terminology" a wide range of methods and approaches in terms of scenario development are in use. Some of them are currently revised or will be replaced by new methods and approaches respectively. The general basis for many of the procedures is the international OECD/ NEA FEP database. Another fixed element of scenario development constitutes expert judgement. In this context, the general opinion arose that systematic approaches should be used whenever possible. It was also recognised, that expert judgement implies some subjective influences which finally cannot be avoided. Therefore, traceability of decisions by expert judgement is of paramount importance. Regarding the matter of comprehensiveness in terms of scenarios and / or FEPs it was concluded, that comprehensiveness can be achieved but it cannot be proved.

8.5 Application and Experience

Since scenario development is intrinsically linked to safety analyses the subject has been addressed in international and national projects for a long time. The involved organisations in

PAMINA took also part in several former international projects, e.g. EVEREST, SPA, and BENIPA, or contributed to international databases or catalogues such as OECD/NEA FEP database and FEPCAT, wherein scenario development or influencing factors as well as the handling of scenarios were of great interest. Moreover, the organisations participate in international studies, working groups like the former PAAG and current IGSC, and workshops.

Hereafter some examples from national projects and working programmes in conjunction with gained experience are listed:

- << The dossier 2005 Argile considered a normal evolution scenario aiming at verifying that the repository fulfils the safety objectives assigned to it. Results of the reference calculation showed that the main barrier for the confinement of the radionuclides (except four radionuclides) is the Callovo-Oxfordian. In addition, a series of sensibility studies were performed taking into account phenomenological analysis and associated uncertainties. >> [Andra]
- << The underlying methodology for scenario identification was applied by Enresa in the most recent Safety Assessment. Enresa has developed its own FEP databases for repositories in granite and clay using NEA FEP database as starting point. FEPs from other Safety Assessment exercises were also included. >> [Enresa]
- << A matrix diagram was used to examine the interactions between FEPs. The matrix diagram
  - addresses FEPs at the conceptual model level and all potential interactions were considered in a systematic manner.
  - is particularly helpful for identifying second-order interactions (i.e. where FEP A influences FEP B via FEP C).
  - has been used to define modelling requirements for new software modules and to assist in packaging assessment work by identifying potential impacts of specific FEPs. >> [NDA]

<< The extended PROSA method has been applied for the safety study underlying to the license application for the closure of the Asse salt mine and the Morsleben Repository for radioactive waste. >> [NRG]

<< In preliminary safety analyses, which have been performed in the Czech Republic so far, conservative parameters more characteristic to altered scenarios then to normal evolution scenario have been used. >> [NRI, RAWRA]

<< The latest safety assessment of Posiva is TILA-99. TILA-99 did not use the concept scenario as defined in the IAEA [IAEA, 2007]. The scenarios in TILA-99 were in fact calculation cases that could be grouped to fit within a few scenarios using “scenario” as defined in the IAEA glossary of terms [IAEA, 2007] >> [Posiva]

<< The PROSA methodology has been applied in the SAFIR 2 report [ONDRAF, 2001]. It appeared necessary to develop a much more detailed assessment basis and an up-to-date

scenario development methodology for the Safety and Feasibility Case 1, which is scheduled to be published in 2013. >> [SCK/CEN, ONDRAF/NIRAS]

As indicated above the participating organisations have gained a lot of experience in scenario development from different activities. The lessons learnt from the experience and activities as presented in the contributions can be summarised as follows:

- Use of more realistic data in future work concerning the evaluation of the normal evolution scenario is envisaged.
- Derivation of altered scenarios in considerations of safety functions as a new option.
- There is a strong influence of expert judgement concerning the results of scenario development.
- Creating of comprehensive FEP lists is very time consuming, large lists are difficult to manage, using and implementing existing FEP list in own database is not a straightforward process.
- Significant effort exists regarding expert judgement of FEPs.
- Interpretations of other national programmes are difficult due to different usage of the terms.

Remarks and lessons learnt from the evaluator view which relates understandably to the work of their respective country are as follows:

- << The main remark regarding the SAFIR 2 report was, that the used approach is over-simplified and does not correctly reflect the reality when considering only two states for addressing the performance of a safety component: either fully-efficient or fully non-efficient. A more accurate approach, considering possible partial degradations of the safety functions has been recommended. >> [AVN]
- << “2001 Clay Dossier” and “2005 Clay Dossier” were provided by Andra and reviewed by IRSN concerning the deep geological disposal. Several remarks arose from the reviews, e.g. the safety analysis doesn’t clearly highlight the key engineered components and their performance levels expected in relation with the safety of the disposal system. >> [IRSN]
- << Scenario development is largely based on expert judgement which is partly accompanied by subjective influence. These subjective influences should be reduced as far as possible. >> [GRS-K]

Finally, it has to be stated, that we can learn a lot from each other and should participate from the developments of our partners abroad, both in a positive and negative sense. Furthermore, it is important to document success and failures with respect to the evolution of a repository along the different stages such as siting, licensing, construction etc. which can have a strong influence on scenario development. Since the evolution of the repository can take a period of several decades, numerous generations will be involved in the entire process, so that comprehensive, suitable, and transparent documentation of successful or unsuccessful developments are vital in order to avoid same mistakes or redundant work.

8.6 Developments

Developments are mostly the result of gained experience from former work and projects, reviews or changed conditions and frameworks. In case of scenario development it was not different. Identified developments from the contributions are listed in the following:

<< International and national reviews of the Dossier 2005 considered that the methodology for scenario development was quite interesting and should be pursued. Furthermore, it was recommended to develop QSA (Qualitative Safety Analysis) prior to scenario development as it was acknowledged that it could be useful for identification of calculation cases. Further safety activities will consider such a methodological development. >> [Andra]

<< Enresa does not intend to make a new Safety Case exercise of a deep geological repository in the near future. Enresa follows the international developments in this field (scenario development) and other fields related to the Safety Case, and can take part in EC R&D projects, but no indigenous work is being done on this topic. >> [Enresa]

<< NDA has carried out work with Bristol University on the application of Bayesian Belief Networks to variant scenarios connected with climate change. Identification of variant scenarios is a basis for future work in this area. >> [NDA]

<< It is expected, that the PROSA procedure for identifying scenarios will be extended by the application of 'safety functions' for future safety studies. And it is also expected, that it will be very useful to present the results of PA-calculations along the lines of safety functions. >> [NRG]

<< Currently top down system described in the document devoted to safety functions is being formed. This system is strictly going from top functions to daughter functions and requirements. At each level of system decomposition it will be tested whether the identified safety function is fulfilled under all external effects from outer systems. >> [NRI, RAWRA]

<< Currently a Safety Case is being performed whereas the definition of scenarios is part of the process report. >> [Posiva]

<< From national and international [NEA, 2003] peer reviews as well as from internal discussions, it appeared necessary to develop a much more detailed assessment basis and an up-to-date scenario development methodology for the Safety and Feasibility Case 1 (SFC 1). Therefore, it was decided to base the identification of altered evolution scenarios on the availability or non-availability of the safety functions instead of on the intactness or failure of the main barriers of the repository system. >> [SCK/CEN, ONDRAF/NIRAS]

Developments from the perspective of the evaluators are:

<< Guidance has to be developed in Belgium. The guidance should first address the purpose and the role of scenarios in a SC for disposal facility (deep geological disposal or near surface disposal). In parallel, some guidance on specific topics has been developed or has to be developed. >> [AVN]

<< The new release of the RFS III.2.f is evolving in the following notions: implementation of the safety functions, reversibility and definition of a disposal concept considering spent fuel. The scenario development must take into account these new trends having a role on the possible performance of the disposal system. >> [IRSN]

<< Currently the “Safety Criteria for the Disposal of Radioactive Waste in a Mine” from 1983 are revised. The revision comprises several requirements in the context of scenario development and dealing with scenarios.

In the framework of a recent launched project the development of scenarios in consideration of safety functions is one of the main tasks. >> [GRS-K]

8.7 Conclusions

The findings from the workshop plus underlying facts, descriptions, and examples from the contributions constitute the foundation for this topic. The main conclusions to the topic "Definition and Assessment of Scenarios" as addressed in the respective chapters, are listed below:

General aspects:

Consensus exists, in terms of the key role of scenario development in safety assessments. In this context, scenario development constitutes the fundamental basis for the further work like the consequence analysis. The scenario development has to indicate in a reasonable manner that all relevant FEPs have been taken into account. Furthermore, the compliance with the regulations has to be shown.

Regulations:

There are different states regarding regulations in the various countries. Some countries have established regulations, others currently work on specific regulations or revise existing ones, and others in turn do not have any regulations at all. Therefore, no consensus whether regulations are needed or not from the view of developers exist. For some participants, guidance in general and regulations in terms of human intrusion and the biosphere are seen as helpful instruments. Others in turn, consider guidance and regulations as a necessary basis. Different opinions exist also, regarding the question of whether the regulator should provide a set of scenarios which have to be investigated by the implementer.

Terminology:

A wide range of definitions and concepts related to scenario development and scenarios exist. Use and meaning of terms differ significantly from country to country. But all of them have in common, that a so called central scenario is considered as a starting position, with appropriate additional scenarios. It was stated, that the definitions provided by the IAEA and OECD/NEA regarding the terms "scenario" and "scenario development" constitute a valuable initial basis which can be modified / adapted according to the respective national conditions.

Another outcome of the discussion was, that there is no need to harmonise the terminology across the different countries, but a common understanding is necessary for communication.

Methodology:

Similarly to the issue "Terminology" a wide range of methods and approaches in terms of scenario development are in use. Some of them are currently revised or will be replaced by new methods and approaches respectively. The general basis for many of the procedures is the international OECD/ NEA FEP database. Another fixed element of scenario development constitutes expert judgement. In this context, the general opinion arose that systematic approaches should be used whenever possible. It was also recognised, that expert judgement implies some subjective influences which finally cannot be avoided. Therefore, traceability of decisions by expert judgement is of paramount importance. Regarding the matter of comprehensiveness in terms of scenarios and / or FEPs it was concluded, that comprehensiveness can be achieved but it cannot be proved.

Application and Experience:

A great deal of experience exists due to the several international projects, studies, working groups and initiatives as well as national projects and working programmes with respect to scenario development. One of the outcomes on the basis of gained experience and cognition were, that safety functions seem to play a great role in connection with scenario development in future. Furthermore the role of expert judgement appears to be a subject for discussion in some nations concerning high effort as well as strong and subjective influence.

Developments:

The main developments identified focus more or less to the consideration of safety functions either in existing methodologies by modifications or by developing new approaches. Developments related to regulation comprise the current revision of existing safety criteria and safety requirements, respectively.

8.8 References

[IAEA, 2007] IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection (2007 Edition). Vienna. Publication STI/PUB/1290.

[NEA, 1992] NEA. "Systematic Approaches to Scenario Development"; Paris, 1992, France

[NEA, 2001] NEA. "Scenario Development Methods and Practice", An Evaluation Based on the NEA Workshop on Scenario Development, Madrid, May 1999, Spain, OECD 2001

[NEA, 2003] Nuclear Energy Agency (NEA), SAFIR 2: Belgian R&D Programme on the Deep Disposal of High-level and Long-lived Radioactive Waste - an International Peer Review, OECD/NEA, Paris, 2003.

[ONDRAF, 2001] ONDRAF/NIRAS, SAFIR 2 – Safety Assessment and Feasibility Interim Report 2, NIROND 2001-06 E, 2001.

9. Human intrusion

9.1 Background/ Introduction

The worldwide favoured option of isolating highly active and long-lived radioactive waste is disposal in deep geological formations. The proof of the safety of such disposal systems has to be demonstrated in a safety case. An essential component in the framework of the safety case is the scenario development, wherein the features, events and processes (FEPs) that affect the evolution of the disposal system have to be identified, and combined to give representative scenarios. In carrying out a safety analysis the possible consequences have to be calculated from the developed scenarios.

The evolution of the disposal system can be affected in principle by natural induced phenomena, anthropogenic phenomena as well as waste and repository induced phenomena. In terms of "anthropogenic phenomena" human activities that can alter the isolation capacity or the site situation of the disposal system are often distinguished from activities that destroy or directly bypass the isolation capacity (section 9.3). The latter activities will be termed as "Human Intrusion" (HI) and are the subject of this document.

The following list includes the key issues, which were subject in most of the discussions of national and international organizations:

- predictability of HI;
- general assumptions and provisions;
- likelihood and probability of HI;
- measures against HI;
- types of HI actions and scenarios;
- anomalies and noticeable features;
- evaluation criteria, exposures, limits, and consequences.

Each of the listed items is discussed in detail in the section 9.4 "Methodology".

9.2 Regulations and Guidelines

Regulations and guidelines are, in general, a worthwhile basis for both the developer and the evaluator. The developer benefits from guidance which indicates how the compliance with provided requirements could be demonstrated. The evaluator can draw on a framework given by regulations that facilitates the review work, assessments etc. of relevant records in the licensing procedure.

Therefore, regulations should not only include requirements that have to be fulfilled by the developer, but also acknowledge inevitable uncertainty about future developments. Moreover, they should offer guidance in areas with great uncertainties about the future that makes uncertainty management difficult. This applies especially to the topic "Human

Intrusion” where accurate predictions are not possible and it is known that human actions can lead to high radiological exposures, for humans and the environment under certain circumstances.

In principle, international guidance is addressed in the respective legal national frameworks. The international guidance gives some recommendations as to how “Human Intrusion” should be treated. These recommendations are understandably, for the most part, rather general and not specific. However, the recommendations constitute an initial basis for the elaboration of specific national rules and guidelines with respect to the topic “Human Intrusion”.

The regulations and guidelines considered in this chapter refer to HI in relation to the disposal of high active waste in deep geological formations. The review of the different contributors to HI has yielded the following:

All in all four of the participating countries, namely: Czech Republic, Finland, France, and UK have regulations or guidelines in place where the subject HI is addressed.

In Belgium, a specific regulatory framework, applicable to both near-surface and geological disposal facilities is currently being developed. A general guide and a number of associated guides, including for HI, already exist for near-surface disposal facilities. This guide will be used when developing the regulation related to geological disposal [FANC].

The existing regulations in Germany include no specific regulatory requirements for HI. These regulations are currently being revised to address the issue of how to deal with HI in the safety case.

Other participating countries like the Netherlands and Spain presently have no regulatory requirements or provisions that directly relate to the topic of HI.

Apart from the above contributors, there are some recommendations to HI from international organisations such as the IAEA, ICRP [ICRP,1998] [ICRP, 2007] and OECD/NEA [NEA, 1995]. In addition to these international recommendations, some national regulating views from European countries like Sweden and Switzerland that do not participate actively in PAMINA, but have an advanced waste disposal programme, will be referenced in this chapter, as required.

It should be noted that guidelines and regulations affect for some part the methodology regarding the treatment of HI in the safety case. Furthermore, it is in the nature of things that HI has in terms of the predictability and associated uncertainties a great influence on both the regulation and methodology. Therefore, it was decided to address the key aspects of HI in chapter 9.4 “Methodology“ including those aspects which actually relate to the task of the regulators.

Outcome of the workshop:

The outcome of the workshop that directly relates to the expectations of guidelines and regulations for HI is addressed as follows:

- The treatment of HI should be addressed in regulations and guidelines provided by the respective responsible authorities.
- Requirements concerning the framework, scope of the investigations, constraints and conditions etc. should be provided.
- The relevant actions e.g. drilling, mining for HI scenarios should also be provided.
- It should be acknowledged that selected HI scenarios can never be complete or comprehensive.
- HI scenarios should be determined on a stylised basis, since a systematic development of HI is not possible.
- It should be a requirement that HI has to be considered in the site selection process (e.g. resources) and in the design phase of a repository (e.g. depth).

There is some information from the regulator part that it will be the task of the implementer to develop a strategy how to deal with human intrusion:

<< SKI (the Swedish Nuclear Power Inspectorate) pointed out that SKB: "… must develop their own strategy for how issues relating to human intrusion should be handled in future safety assessments." >> [SKB, 2006].

9.3 Terminology

There are many national and international references which describe the study of human impacts on repositories of radioactive waste. The terms used for those impacts vary widely, e.g. human events, intrusion events, future human actions, inadvertent actions, human intrusion etc. Some of them are similar and some are slightly different in their meaning. In this context, human intrusion constitutes a subset of the overall term human action. Human actions can be divided into those that influence the environment of the disposal system, e.g. alteration of the groundwater flow regime, and those which directly impair or bypass the barriers or safety functions of the disposal system e.g. drilling of a borehole through the waste emplacement area. Further examples for both types of human actions can be found in work carried out by NRG. As mentioned in section 9.1, human actions of the latter type which are caused inadvertently, i.e. without knowledge of the repository site and the hazard of the waste, are called human intrusion.

Given the fact that there are different methodologies, approaches and procedures for addressing human intrusion in safety cases, it is understandable that the meaning and also the number of terms and terminologies vary significantly. The use of different terms and additional concepts accompanying the topic of "Human Intrusion" like deliberately, intentional, unintended, stylised, future human actions etc. does not help and may even lead to some confusion. At the very least it makes the communication on a national as well as international level more difficult. Therefore, international bodies, like IAEA, ICRP and OECD/NEA aim for a common harmonized terminology and provide glossaries and definitions in the area of nuclear technology and waste disposal. However, in this case, the IAEA glossary does not provide definitions for human intrusion, human action, inadvertent action or other related terms. In this context the following definitions are given from ICRP and OECD/ NEA:

- << A human action affecting repository integrity and potentially having radiological consequences is known as human intrusion. >> [ICRP, 1998]
- << ... by definition, an intrusion event bypasses some or all of the barriers that have been put in place as part of the optimisation of protection. >> [ICRP, 1998]
- << Future human actions of concern are those occurring after repository closure that have the potential to disrupt or impair significantly the ability of the natural or engineered barriers to contain the radioactive wastes. >> [NEA. 1995]

Examples from references of national organisations that do not actively participate in RTDC-1 of the integrated project PAMINA are as follows:

- << ... future human activities are activities that may take place in the vicinity of the disposal site at some time in the future and which may affect the performance of the repository by by-passing or affecting the characteristics of the engineered and natural barriers. >> [SKI, 1999]
- << Intrusion is defined as “inadvertent human actions that impair the protective capability of the repository” >> [SKB, 2006]

There are few definitions relating to HI from the contributors, but the terms and definitions used correspond more or less with the terminology from international bodies. The main observations from the contributors can be summarised as follows:

- Definition of HI in line with regulations [ASN, 2008]: The events connected to the human activity include direct or indirect human interventions (e.g. drillings) [Andra].
- No formal definition for HI is given, but the definition provided by NEA is applicable [Enresa].
- Distinction between HI and Future Human Actions (FHA) is made. A description to HI scenarios is given [GRS-BS].
- Used terms correspond mostly to the terminology proposed by international bodies like IAEA, OECD/ NEA [NDA, NRI, Posiva].
- No terms, definitions etc. related to HI were given [NRG].
- Definitions of terms related to human intrusion are provided. The definitions to FHA and inadvertent actions are used from a NEA report. A definition to HI is also included in the contribution of [SCK/CEN, ONDRAF/NIRAS]
- Some concepts like SF, disposal system etc. are described. A definition to HI is also included in the contribution of [FANC].
- There are no definitions and descriptions of terms and concepts related to HI in the legal regulatory frame [GRS-K].

- Several definitions, terms and concepts regarding the HI topic were listed for the most part from a NEA document and from recent developments. This includes definitions to FHA, HI, stylized scenarios, inadvertent actions and intentional actions [GRS-K].

As a result, only fiver out of ten contributors provide a definition for HI:

- << Human action causing partial or full degradation of one of several safety barriers of the disposal system, and that may expose the author of the intrusion (named as “the intruder”) or the surrounding population to a radiological risk. >> [FANC]
- << ... inadvertent action that has the potential to disrupt or impair significantly the ability of the natural or engineered barriers to contain radioactive waste >> [SCK/CEN, ONDRAF/NIRAS]
- << In a similar way, the ASN guide considers that after closure of the repository, some uncertain events, but plausible, natural or connected to human actions, can disrupt or perturb the evolution of the repository system and consequently modify the migration of radioactive substances. Certain situations resulting from these events could possibly lead to individual exposures higher than those associated with the reference situation. >> [Andra].
- << Human intrusion scenarios comprise those future human actions that lead to a direct penetration of a repository and damage the barriers within the backfilled and sealed repository area and the host rock. These may either cause direct releases into the biosphere or impair the barrier system of the repository or its safety functions. >> [GRS-BS]
- << Human intrusion (HI) is understood as any human activity following the closure of the repository mine that will directly damage the barriers within the backfilled and sealed mine workings and the isolating rock zone. >> [GRS-K]

It should be pointed out that the above listed definitions of both national and international organisations are rather different in terms of the wording. However, the general statement that human actions involve a direct damaging of barriers is more or less the same.

Outcome of the workshop:

Like for other topics of treated in this handbook, it would be a great challenge to harmonise the used terminology relating to HI across the participating organisations and countries. There is no mandatory reason for it. However a common understanding of used terms is necessary in order to avoid misunderstandings. As a result of the workshop the participants agreed on the following description with respect to HI:

Description of HI:

HI can be understood as human actions which have the potential to directly jeopardise the isolating capacity of the barriers of the disposal system and therefore might have radiological consequences.

Additional notes:

The term “disposal system” in the description above, can be defined as the combination of engineered and natural barriers that isolate radioactive waste when disposed in geological formations (this definition corresponds to a large extent to the provided definition in the US Environmental Standards for Disposal 40 C.F.R. § 191.12 Definitions).

Other terms:

It was further agreed by the participants that other terms associated with HI will be those adopted by the NEA [NEA, 1995]. These include, for example, the following terms relating to unintended and intentional actions:

- Unintended actions: << Those in which either the repository or its barrier system are accidently penetrated or their performance impaired, because the repository location is unknown, its purpose is forgotten, or the consequences of the actions are unknown. >> [NEA, 1995]
- Intentional actions: << In contrast, if future intruders are aware of the waste and the consequences of disturbing the repository or its barrier system, then their actions are intentional. >> [NEA, 1995]

Another commonality relates to stylisation of HI scenarios. Stylised HI scenarios are composed of regulatory provisions and should take into account the specific conceptual design of the disposal system as well as present site conditions.

9.4 Methodology

This chapter primarily considers the treatment of HI from a methodological point of view as well as safety issues. In addition, regulatory aspects as described in chapter 9.2 will be also discussed in this chapter due to the close connection of required/ expected regulations and the methodology with respect to the handling of HI.

The concept of concentrating and isolating the radioactive waste in a disposal system involves an increased risk of radiation exposure in the case of HI. Otherwise, the prediction of safety cases in terms of when, where and how future generations might intrude into the disposal system is strongly limited even in the short-term after closure of the repository and will be impossible as time goes by. This in turn determines on the one hand the requirements of regulations and guidelines, and the development of the methodology for the treatment of HI in the safety case on the other.

Methodological viewpoints should demonstrate the strategy of how to deal with possible future impacts on the disposal system caused by human beings and the underlying conditions, assumptions, arguments and provisions for analysis.

Regulatory viewpoints should provide the framework and the expected scope for the investigation of HI and should also give guidance on how to interpret calculated consequences.

Different key aspects for the treatment of HI are considered e.g. assumptions, the likelihood of such events, possible measures against HI, assessment of consequences etc. (cf. also chapter 9.1.2), and presented in this section.

9.4.1 Predictability of HI

There is a broad consensus that human behaviour cannot be predicted with the necessary accuracy over the relevant timescales for radioactive waste disposal. There are several examples of this conclusion in the following text from international and national organisations, as well as from the Project participants:

- << The representation of future human behaviour in assessment models is necessarily stylized, as it is not possible to predict behaviour in the future with any certainty. >> [IAEA, 2006]
- << The inherent difficulty in predicting human actions and our own inability to delve into the far future will always limit the ability to make definitive statements about the risks to future societies from the disposal of long-lived wastes. >> [NEA, 1995]
- << The prediction of future human actions is fraught with uncertainty >> [NEA, 1995]
- << ...there is little or no scientific basis for predicting the nature or probability of future human actions... >> [ICRP, 1998]
- << Future human actions that can affect the safety of a repository involve questions concerning the evolution of society and human behaviour. These are questions that cannot be answered by conventional scientific methods. For example, it is not possible to predict knowledge that does not exist today, and knowledge is judged to be a key factor in this context. >> [SKB, 2006]
- << Swiss regulations (HSK and KSA, 1993) acknowledge the impossibility of predicting future human actions, but do require events and processes that could disrupt a repository to be considered in developing scenarios. >> (note that this statement refer to Swiss regulations) [SKI, 1999]
- << …we conclude that there is no technical basis for predicting either the nature or the frequency of occurrence of intrusions. >> [NAS, 1995]
- << Given the impossibility to predict future human actions and technologies, the assessment of the impact of human intrusion will be made by means of arbitrary stylized scenarios. >> [FANC]
- << ...the evolution, way of life, and behaviour of the society, inclusive human intrusion, cannot be predicted over time frames, which have to be considered for the isolation period of radioactive wastes. >> [GRS-K]
- << There is agreement that the development of the mode of live and the behaviour of mankind, or social communities can only be assessed over a short time frame of few generations. >> [GRS-BS]
- << Assessments of the post-closure safety of a repository typically extend over periods of hundreds-of-thousands of years. Over this period of time, the form of human society will change in a manner that cannot be predicted. >> [NDA]

- << It is extremely hard to predict the social changes and the technologies that will be accessible to future generations. In accordance with the recommendations of [ASN, 2008] (ex basic safety rule RFS.III.2.f.), this type of uncertainty was dealt with by assuming that their technical level will be equivalent to our own >> [Andra].

Outcome of the workshop:

As a result from the contributions, other references and the discussion at the workshop, the participants agreed unanimously to the following statement:

HI cannot be predicted over timescales which are relevant or of interest for the disposal of high active waste.

9.4.2 General assumptions and provisions

In the following there are some general assumptions and provisions which can be attributed to the fact that HI is unpredictable. These general assumptions and provisions can serve as a basis for the elaboration of rules and guidelines that provide the framework for the treatment of HI.

Unintended and intentional actions:

A distinction is often made whether the human intrusion will be performed intentionally or unintentionally. The difference indicates that in the case of an intentional intrusion the society/intruder is aware about the location of the repository and the associated hazard. An unintended intrusion in turn indicates that the society/intruder has no information and knowledge about the disposal site and the radiological hazard of the emplaced waste. There are some other terms for intentional intrusion and unintended intrusion in use. The different terms are discussed in chapter 9.3 “Terminology”.

For many countries it is only the unintentional human intrusion that has to be taken into account in safety cases. The intentional human actions are for some part considered in terms of protection goals (cf. [FANC]) but will be generally excluded from safety assessments. Examples from the contributors which include statements about unintentional and intentional actions are as follows:

- << ...it is necessary to fix a date before which no involuntary human intervention can occur because of the preservation of the memory of the existence of the repository. >> [Andra]
- << Enresa has adopted NEA´s recommendation and only inadvertent human intrusions are analysed. >> [Enresa]
- << ...both types of intruders should be protected through appropriate measures to be taken by the operator. However, as it is impossible to totally prevent deliberate intruders from accessing the waste, the main concern for determining the measures related to the intrusion problematic will focus on the protection of the inadvertent intruder. >> [FANC]
- << From the human intrusion scenarios, usually those initiated by an intentional intrusion are not included as they are in the responsibility of the respective society and the

intruder is in charge of the radiological implications [NEA, 1995]. In case of inadvertent human actions the knowledge of the repository has to be lost at the time of occurrence. >> [GRS-BS]

- << It is exclusively considered the inadvertent human intrusion. Scenarios which describe the intentional human intrusion into the barrier system are not considered. These are put in the responsibility of the respective acting society. >> [GRS-K]
- << Human intrusion could be intentional or inadvertent. Intentional human intrusion, that is deliberate intrusion into the repository in the knowledge that it contains radioactive materials, is generally considered to be the responsibility of the society taking the action, and UK regulatory guidance states that the associated risks need not be considered in a performance assessment [EA, 1997]. >> [NDA]
- << For the treatment of human intrusion the document states that only inadvertent intrusion, most often associated with a loss of memory of the existence of the repository, has to be taken into account... >> [SCK/CEN, ONDRAF/NIRAS]
- << The human origin actions concern only inadvertent intrusions. These would be due to a loss of the memory of the repository after 500 years. After this date it is considered inadvertent intrusion. The possible means of maintaining a record of the repository were presented in the Dossier 2005. It nonetheless remains highly likely that on a million year time-scale the memory of the repository, of its location and of its purpose, could be lost >> [Andra].

Outcome of the workshop:

The above examples and the results from the discussion at the workshop lead to the conclusion that only unintended human intrusion has to be taken into account. Intentional human intrusion, i.e. human actions with knowledge of the disposal site and the hazardous waste, are the responsibility of the society taking that action.

HI cannot be ruled out:

The fact that human actions cannot be predicted with adequate accuracy for the required timeframe does not imply that those actions can be excluded from safety considerations. In fact, the contrary is the case.

With regards to the loss of information and termination of institutional control it was often stated by contributors that HI cannot be ruled out. Examples that reflect this context are:

- << The safety assessment methodology has to be developed based on the assumption that human intrusion cannot be ruled out after the release of the institutional control (postulated loss of memory of the repository existence). >> [FANC]
- << However since human intrusion scenarios, after loss of the information about the repository, cannot be ruled out, they have to be assessed within the overall safety case. >> [GRS-BS]
- << Inadvertent human intrusion into the repository system cannot be excluded totally, after a loss of information about the repository in the far future. >> [GRS-K]

- << It cannot be guaranteed, however, that intrusion might not occur at some time in the future after administrative controls have been discontinued. >> [NDA]
- << Inadvertent intrusion can be assumed to be excluded during the period of institutional control which can last for 100 or 300 years. ... However at longer time scales the loss of information about the repository can take place. >> [NRG]
- << In spite of all the countermeasures, it cannot be completely ruled out that human being may, intentionally or inadvertently, intrude into the repository in the future. >> [Posiva]
- << The ASN guide fixes a date before which no involuntary human intervention can occur because of the preservation of the memory of the existence of the repository. This memory depends on the perpetuity of the measures which can be implemented during the filing of the institutional documents resulting from the regulations... In these conditions, the loss of memory of the existence of the repository can be reasonably situated beyond 500 years. This value of 500 years is retained as earlier date of occurrence of a human intervention >> [Andra].

Outcome of the workshop:

There was a common consensus that HI has to be considered when discussing the safety of the disposal system. However, there were different opinions about where and how HI has to be treated in the safety case. There was overall agreement that this depends on the respective conditions and regulations in the different countries.

HI cannot be developed systematically:

The evolution of the disposal system is in principle determined by natural phenomena, anthropogenic phenomena and waste and repository induced phenomena. The evolution is usually considered in safety assessments by a so called central or reference scenario that reflects in most cases the expected evolution of the disposal system and a set of alternative scenarios which include additional potential evolutions. These scenarios should be developed in a systematic, transparent, and traceable manner through a structured analysis of relevant FEPs that are based on current and future conditions of the disposal site. Unfortunately, this requirement cannot be applied to HI scenarios due to the unpredictability of social behaviour and human actions. The following examples reflect this conclusion:

- << … a systematic development of the scenario group human actions is not possible. However since human intrusion scenarios, after loss of the information about the repository, cannot be ruled out, they have to be assessed within the overall safety case. >> [GRS-BS]
- << ...a systematic scenario development, like for natural phenomena, is impossible for human intrusion phenomena. >> [GRS-K]

Outcome of the workshop:

As a result from the discussion at the workshop the participants concluded the following:

It is not possible to derive HI scenarios in a systematic way as for other scenarios.

HI scenarios should be treated separately from the other scenarios:

Another issue is the consideration of HI scenarios in connection with the treatment of other scenarios such as the central scenario (reference scenario) and altered scenarios. In this context there are some references, reports, documentations, etc. that require human actions and HI scenarios to be treated separately. Examples of this are:

- << Because the assumed intrusion scenario is arbitrary and the probability of its occurrence cannot be assessed, the result of the analysis should not be integrated into an assessment of repository performance based on risk, but rather should be considered separately. >> [NAS, 1995]
- << The human intrusion scenarios were distinguished from the other scenarios as exposure is the direct or indirect result of a deliberate human action in or close to the geological formation where the waste is stored. >> [NRG]
- << Scenarios involving unpredictable future human actions leading to the partial or full degradation of the isolation and/or confinement properties of disposal facilities (amongst which human intrusion) have to be considered independently from the other types of scenarios (such as the reference evolution scenario / altered evolution scenarios / “what-if?” scenarios) >> [FANC]
- << This intrusion could have a variety of causes and consequently take various forms. The typology exposed in the Dossier 2005 Argile was inspired by the cases proposed in basic safety rule RFS.III.2.f. The human intrusion was treated separately from other scenarios. A specific « borehole » scenario considered two cases (an immediate impact due to operation during drilling and a differed impact resulting from the abandonment of an exploration borehole badly sealed) >> [Andra].

The participants at the workshop concluded the following:

HI scenarios should be treated separately from the other scenarios resulting from natural events. In fact, HI should be already considered in the site selection process and in the design phase of a repository.

Stylised HI scenarios should be provided:

As previously stated the HI scenarios have to be provided in a stylised way. Stylised scenarios related to HI are taken as selected scenarios which have to be derived on the basis of specific repository plans and site conditions. Stylisation comprises a set of conditions and provisions that should allow the developer to analyse the provided scenarios according to the respective requirements of the responsible authorities. Providing stylised scenarios is strongly related to rules and guidelines and is therefore one of the tasks of the regulator. In the following are some examples from international and national references as well as from the contributors that refer to stylisation and respective regulation:

- << Because the occurrence of human intrusion cannot be totally ruled out, the consequences of one or more typical plausible stylised intrusion scenarios should be considered by the decision-maker to evaluate the resilience of the repository to potential intrusion. >> [ICRP, 1998]

- << Irreducible uncertainties related to the biosphere and future human actions are treated by examining stylised and illustrative cases. >> [NAGRA, 2002]
- << Given the impossibility to predict future human actions and technologies, the assessment of the impact of human intrusion will be made by means of arbitrary stylized scenarios. >> (cf. also section 9.4.1) [FANC]
- << … the spectrum of human intrusion scenarios to be considered in a safety case should be confined and that the regulator should establish the boundary conditions for the development of such scenarios. >> [GRS-BS]
- << ...selected scenarios, referred to as reference scenarios (stylised scenarios), have to be established and analysed. >> [GRS-K]
- << ...the following aspects are essential for describing and analysing the reference scenarios: intrusion area concerned, point in time for intrusion, waste category concerned, exposure type and exposure path, exposed group of people and spatial extent of a potential contamination. >> [GRS-K]
- << The human intrusion scenario is taken into account as a regulatory demand and it is not derived from FEP analysis. >> [Posiva]
- << Andra's approach on human intrusion considers the applicable guides and regulations issued by the Nuclear Safety Authority (ASN). The 2008 guide [ASN, 2008] suggests in its Annex 2, various altered situations connected to human activity to consider in future safety cases with regards to their likelihood >> [Andra].

Outcome of the workshop:

The outcome of the discussion at the workshop was already mentioned in relation to the expectations of guidelines and regulations for HI. It was agreed that HI scenarios should be determined on a stylised basis, since a systematic development of HI is not possible (cf. chapter 9.2).

Today´s technology and practice should be assumed:

A set of assumptions is needed for both the selection and the analysis of stylised HI scenarios. The assumptions derive from issues such as data or information about drilling techniques and usual borehole dimensions. Since these data and techniques cannot be predicted over the timescale considered for intrusion, the status quo with respect to knowledge and technology is often assumed. These circumstances are reflected in the following statements from the contributions:

- << The characteristics of the borehole are based on the RFS III.2.f recommendation stating that « the level of technology used is the same as today »...>> [Andra]
- << For the evaluation of human intrusion scenarios in the safety case scenarios should be consulted that are based on today's social conditions and state of the art in science and technology. >> [GRS-BS]

- << The reference scenarios have to be selected on the basis of today´s social conditions, customs, behaviour patterns and state of the art in science and technology. >> [GRS-K]
- << To avoid any need to speculate how society and technology will evolve, the approach to the assessment of the human intrusion pathway is therefore to develop scenarios based on current technology and understanding ... >> [NDA]
- << ... only inadvertent intrusion, most often associated with a loss of memory of the existence of the repository, has to be taken into account and that the same level of technology as at present can be assumed. >> (according to Franco-Belge Working Group, 2004, [FANC, 2004]) [SCK/CEN, ONDRAF/NIRAS]

Outcome of the workshop:

The participants of the workshop concluded that HI scenarios should be developed on the basis of today´s available technology and social behaviour.

9.4.3 Likelihood and probability of HI

The terms “likelihood“ and “probability“ are almost always mentioned in the discussion of HI. Actually, these terms mean nearly the same, but they are quite often used in a different context. The term “likelihood“ relates to a more qualitatively evaluation to the possibility that HI can take place and it is often used in connection with the requirement for reducing the risk of a HI event. On the other hand, the term "probability" is more used in a quantitative manner, concerning the discussion on how probable it is that a specific HI event occurs. This is known as the occurrence probability. The following are examples from an international organisation, a national organisation and a participating organisation that reflect the view of reducing the likelihood or risk of HI:

- << To isolate the waste from the biosphere and to substantially reduce the likelihood of inadvertent human intrusion into the waste >> [IAEA, 2006]
- << By locating the repository at a site where the host rock can be assumed to be of no economic interest to future generations, the risk of human intrusion is reduced. >> [SKB, 2006]
- << In a similar way, the localisation of the site in the Meuse/Haute-Marne area is chosen, in coherence with the 2008 guide released by French Nuclear Safety Authority, [ASN, 2008] so as to avoid zones which can present an exceptional interest in terms of subterranean/underground resources >> [Andra].
- << ...the main approach to dealing with the human intrusion issue for a geological disposal facility lies in the measures taken for limiting the likelihood of human intrusion events. >> [FANC]

The reduced likelihood of HI is often addressed in connection with information preservation, institutional control and avoiding sites with valuable resources. These issues are close to possible measures against HI and therefore will be discussed in the next chapter.

Some contributors mentioned that the likelihood of HI into a deep geological repository is low or possibly may be low. The following examples highlight this:

- << Therefore, it is necessary to assess such events and estimate their consequences, even though their likelihood may be low. >> [NDA]
- << It was considered in the preliminary safety assessment of the Czech concept of Deep geological repository that the probability of human intrusion will be significantly reduced by meeting site selection criteria. >> [NRI]
- << Even if information about the repository were lost, it is very unlikely that someone would intrude or drill into the repository by accident. >> [Posiva]

It should be noted that it seems to be somewhat contradictory that on one hand human behaviour and therefore HI cannot be predicted, and on the other hand it is believed that the likelihood of HI into the repository is low and furthermore that the likelihood can be reduced. The rationale behind this is that the likelihood cannot be reduced in the long run if the actual initiating actions, events, processes, motivations etc. are unknown.

Concerning the probability issue the contributors views are rather different. The following quotations and statements reflect this:

- << Enresa has focused on the definition and consequence analysis of a human intrusion event (or scenario), and no efforts are done to quantify the probability of the human intrusion. >> [Enresa]
- << ...the probability of occurrence of a HI event could be considered as extremely low (and thus the resulting risk acceptable)... >> [FANC]
- << In a semi-quantitative approach the probabilities of occurrence of the scenarios and their radiological consequences had been classified for each generic repository. >> (according to a study of the BfS) [GRS-BS]
- << Protection criteria for such activities are not prescribed, since neither the probability nor the type of impacts can be assessed with an adequate degree of reliability. >> (according to the draft requirements from the BMU) [GRS-K]
- << It is difficult to assess the human intrusion pathway comprehensively, as the range of phenomena to be considered is difficult to define, and both the impact on the repository and its environs, and the probabilities of occurrence, are difficult to determine. >> [NDA]
- << ... it was decided that the probability of human intrusion is negligible and human intrusion will not be evaluated. >> [NRI]
- << Determination of the probability of the scenarios >> (according to the PROSA methodology) [NRG]
- << The working group of Nordic safety authorities, which discussed and drafted safety criteria for high-level waste disposal, concluded that the estimation of probabilities and consequences of human intrusion is very approximate or speculative. >> [Posiva]

Outcome of the workshop:

Again, taking into account that human behaviour cannot be predicted, the majority of participants at the workshop conclude that it is not possible to derive occurrence probabilities for HI events.

It should also be mentioned that investigations were carried out in order to obtain some estimates of the probability for HI in certain areas based on historical drilling/deep exploration data for that area. For example UK aims to minimise the likelihood of HI by avoiding areas where they has been a history of drilling (e.g. for water or mineral resources).

9.4.4 Measures against HI

The treatment of HI in the safety case calls for the identification and investigation of possible measures that can prevent or hamper such actions or mitigate their consequences. In this context, almost always the same questions arise regarding the effectiveness, effective period and reliability of measures against HI. Another issue in some cases is the requirement that measures should not influence each other and that they should not impact to other safety concern.

Some of the measures should be considered and implemented in due time, in particularly those which relate to the site and concept of the disposal system. For example, if avoiding sites with valuable resources is one of the issues in the concept of measures, then this point has to be addressed in the site selection process.

In the following are some general aspects to measures against human actions that reflect more or less the brief introduction above:

- << Future human actions can adversely impact radioactive waste disposal systems; these actions must, therefore, be considered both in the siting and design of waste disposal systems, and in assessments of their safety. >> [NEA, 1995]
- << Measures for preventing human intrusion need to be taken as early as possible in the development of a project and have to be considered at all stages of the development (e.g. site-selection, design…) even though some stages may be more critical than others. >> [FANC]
- << … scenarios need in particular be considered during planning and designing of the repository in order to identify appropriate counter measures. >> [GRS-BS]
- << It is suggested that events of inadvertent human intrusion shall already be taken into account in the site selection process and the planning and design phase of the repository system. >> [GRS-K]
- << ...the regulator will pay a particular attention to the set of measures proposed by the developer ... for preventing human intrusion ... for limiting the differed radiological consequences... >> [FANC]
- << For each measure taken to prevent HI intrusion, it is in any case essential to verify if it could not be unfavourable to other safety considerations. >> [FANC]
- << Measures against human intrusion are hardly to determine, due to the unpredictability of future activities at the repository site. Apparently, there are only few measures, such

as the deep geological disposal and information preservation, which are suitable to prevent human intrusion for a certain time or make it at least difficult. >> [GRS-K]

- << Due to its conception and assigned safety functions, the repository can be partly protected from drilling by its fractioning, with parts made hydraulically independent of the others, which would prevent propagation of the drilling effects beyond one or more seals. The radionuclide immobilisation function also plays a role in supplementing the other repository safety functions, which could be more directly affected by the drilling. In the situation of a borehole crosscutting the repository, the seals revealed to play a role in limiting the hydraulic perturbation due to the borehole. As a consequence, the amount of radionuclides reaching the borehole was reduced to the nearest “modules” or “compartment” of the disposal >> [Andra].
- << The following aspects should be considered when discussing measures against human intrusion: Measures, that:
  - hamper or make it difficult to intrude;
  - reduce the interest for the intrusion in relevant depth of the repository in a geological formation;
  - preserve the information for a long period on the site and the potential hazard of the repository;
  - facilitate the recognition of the hazard based on the repository before, during and after an intrusion;
  - restrict the potential radiological consequences in case of an intrusion;
  - retard the point of an intrusion as long as possible >> [GRS-K].

- << In spite of all the countermeasures, it cannot be completely ruled out that human being may, intentionally or inadvertently, intrude into the repository in the future. >> (according to [Vieno, 1992]) [Posiva]

Outcome of the workshop:

Results from the discussion of the workshop to general aspects of measures against human actions are as follows:

- Since HI cannot be predicted, the consideration of appropriate measures against HI is limited.
- HI has to be considered in the site selection process and in the design phase of a repository.
- If HI scenarios are examined, then the effectiveness of specific measures should be evaluated, e.g. the construction of compartments in the emplacement area in order to reduce the amount of radionuclides that can be affected by HI events.
- Measures themselves must not compromise other safety concerns of the repository and measures should not counteract each other.

In principle, there are three main types of measures that can be observed from the contributions and other national and international references. These types relate to measures that inform, control and alert society and possible intruders, make it difficult or reduce the interest to intrude and limit the consequences of an intrusion. The first two types refer to measures which take place before and during an action whilst the latter type refers to actions that have already taken place (after an intrusion). In the following different measures from the contributions are listed and discussed:

Avoiding resources:

As mentioned in section 9.4.3 the issue likelihood is often discussed in connection with resources at the disposal site. There are several examples from international organisations, national organisations and participating organisations which state that the likelihood of HI can be reduced if the disposal system would be located away from valuable resources. Some require the exclusion of sites with exploitable resources:

- << Consideration will be given to locating the facility away from known underground mineral, geothermal and water resources so as to reduce the risk of human intrusion into the site and the potential for uses of the surrounding area that are in conflict with the facility. >> [IAEA, 2006]
- << Location away from known areas of underground mineral resources is desirable to reduce the likelihood of inadvertent disturbance of the geological disposal facility and to avoid resources being made unavailable for exploitation. >> [IAEA, 2006]
- << Furthermore, the absence of any currently recognised and economically viable natural resources and the lack of conflict with future infrastructure projects that can be conceived at present reduces the likelihood of inadvertent human intrusion. Finally, appropriate siting ensures that the site is not prone to disruptive events and to processes unfavourable to long-term stability. >> [NAGRA, 2002]
- << The reduced likelihood and consequences of human intrusion is supported by (i) the preservation of information about the repository, (ii) by the avoidance of resource conflicts (i.e. the absence of viable natural resources in the area proposed for the repository), and (iii) by the compartmentalisation of the repository and the solidification of the wastes. >> [NAGRA, 2002]
- The reduced likelihood is supported by the choice of the site ("chosen so as to avoid zones which can present an exceptional interest in terms of subterranean/underground resources"), by the depth of the repository (more than 200 m so that the safety is not affected by common sub surface human intrusion), by its conception and assigned safety function, and by the preservation of the memory (500 years according to regulations) [Andra].
- << For geological disposal of high-level and long-lived waste, the absence of natural resources in the vicinity of the repository combined with the implantation of the repository at sufficient depth are the two key features for reducing the probability of a HI event. >> [FANC]
- << The choice of an appropriate site and host rock (lower drilling frequencies can be associated with rocks that are not of economic significance) >> [NDA]

- << ... a site with exploitable natural resources should be excluded already in the selection site process [STUK, 2001]. >> [Posiva]

Outcome of the workshop:

It was agreed by the participants at the workshop that sites with valuable resources should be avoided in order to reduce the likelihood of HI. There were some reservations as to whether the likelihood can be really reduced over timeframes considered in safety assessments. The main issues of the discussion included:

The reduction of the likelihood of HI through selecting a disposal site with no valuable materials or substances includes the assumption that future generations have the same requirements about needs and resources, as the present generation. This may not necessarily be the case given the long timescale for the isolation period of high active waste. There are some doubts, whether it can be really assumed that today´s habits and needs are applicable for the entire demonstration period for a safety case. However, the real situation at a specific time cannot be predicted, and secondly it can be assumed with sufficient reliability that habits and needs will not change dramatically in the near-term. So that the assumption of the reduction of the likelihood of HI by avoiding sites with valuable resources from today´s perspective is only valid for a certain period of time shortly after repository closure. On the other hand, a geology that mainly consists of materials occurring in large amounts near the surface can be expected to make intrusions less attractive over long time periods. The avoidance of sites with valuable resources that could attract human actions can be compared to the measure of information preservation (see below) which is assumed to prevent unintended HI for at least several hundred years.

Depth of the repository:

The worldwide favoured option for high active waste disposal is the emplacement of such wastes in deep geological formations. The envisaged depth is about several hundred metres below ground in most of the concepts of the different countries. This design option limits from a today´s perspective the number of

- kinds of actions e.g. drilling, leaching and excavation;
- motivations e.g. exploration, exploitation, mining, disposal;
- groups of persons which have the intention, means and resources for such an endeavour.

The following are some examples from the contributors that consider the depth of the repository in connection with HI:

- << For geological disposal of high-level and long-lived waste, the absence of natural resources in the vicinity of the repository combined with the implantation of the repository at sufficient depth are the two key features for reducing the probability of a HI event. >> (cf. also “Avoiding resources”) [FANC]
- << The location of the facility at sufficient depth to reduce the probability of human disturbance (drilling frequency decreases with depth of rock penetrated) >> [NDA]

- << ... placing the waste deep underground is a robust method of reducing the potential for, and likelihood of, human intrusion ... >> [NDA]
- << With respect to the type of formation to be used for radioactive waste disposal, it was felt that storage at greater depths is the most important factor for reduction of the effects of human intrusion. Disposal at great depths might also reduce the probability of human intrusion. >> [NRG]
- << The repository shall be located at a 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. >> (according to Finish regulations) [Posiva]
- << The ASN guide recommends the site to be chosen so that the depth retained for the emplacement of the waste repository allows to guarantee that the safety of the disposal system will not be affected in a significant way by the phenomena of erosion (in particular following a glaciation), by the effect of an earthquake, or by the consequences of "commonplace" human intervention (e.g. sub-surface) >> [Andra].

Outcome of the workshop:

The participants of the workshop concluded unanimously that a sufficient depth of the repository is one of the most appropriate measures against HI.

Institutional control:

As previously indicated, there is a strong relationship between preservation of information and maintaining awareness of that information. The requirement of institutional control is seen as a measure in order to prevent people taking some adverse actions at the disposal site and to keep future generations aware about the location and the associated hazard. Active and passive institutional control is often distinguished. Active institutional control involves limitations on access to the disposal site and its use. Passive measures include organised systems of information conservation and site marking.

Analogous to the issue of information preservation, the same questions arise about the required timeframe for institutional control and how long people can rely upon this measure from a safety point of view. Again, these questions relate to the task of the regulator. The first question about the required timeframe of institutional control is often discussed in connection with one of the main principles, namely to manage radioactive waste disposal without imposing undue burdens on future generations. The answer to the second question depends largely upon the specifications to the first question. However, the duration and effectiveness of institutional control cannot be predicted over all times.

Statements from international organisations and from participating organisations reflect some specific issues in connection with institutional control:

- << Geological disposal facilities do not rely on long term post-closure institutional control as a passive safety function. Nevertheless, institutional controls may contribute to safety by preventing or reducing the likelihood of human actions that could inadvertently interfere with the waste, or degrade the safety features of the geological disposal system. Institutional controls may also contribute to increasing the societal acceptability of geological disposal. >> [IAEA, 2006]

- << ...the Commission recognises that institutional controls maintained over a disposal facility after closure may enhance confidence in the safety of the disposal facility particularly by reducing the likelihood of intrusion. >> [ICRP, 1998]
- << The most effective countermeasure to inadvertent disruptive actions is active institutional control of the surface environment above and for some distance around the disposal site. >> [NEA, 1995]
- << However, active institutional control cannot be relied upon over the timescales for which the waste presents a potential hazard. >> [NEA, 1995]
- << The concept should include a multiple barrier system, and rely on passive repository evolution without institutional control beyond a given timeframe (500 years). [JORF, 1991] >> [Andra]
- << The 2008 guide [ASN, 2008] (ex RFS.III.2.f) indicates that for this type of situation (HI), it is necessary to fix a date before which no involuntary human intervention can occur because of the preservation of the memory of the existence of the repository. In these conditions, the loss of memory of the existence of the repository can be reasonably situated beyond 500 years. This value of 500 years is retained as earlier date of occurrence of a human intervention. The definition of the characteristics of the situations of human intervention retained is based on the following hypotheses: the existence of the repository and its location are forgotten and the level of technology is the same as today. >> (Andra)
- << In this human intrusion scenario it is assumed that 500 years after repository closure, when the institutional control period has passed there are mining activities in the area of the repository. >> (cf. Chapter 9.4.5) [Enresa]
- << Enresa considers that human intrusions are possible as soon as institutional control ends. >> [Enresa]
- << The long-term safety of the final repository must not be based on active monitoring and maintenance measures, excluding a period of at least 500 years following decommissioning, during which current estimates predict that the competent offices will be able to preclude all human activities in the vicinity of the final repository which could threaten the permanent containment of the waste. >> [GRS-K]
- << Inadvertent intrusion can be assumed to be excluded during the period of institutional control which can last for 100 or 300 years. Thereafter a period of administrative control can be foreseen during which deep excavations or drillings at the repository site will be forbidden. However at longer time scales the loss of information about the repository can take place. >> [NRG]
- << Recently in a draft update of the YVL Guide 8.4 it is stated that human intrusion scenarios need to be considered starting only after 200 years have passed from the closure of the repository, as some credit is taken on institutional control and preservation of information about the repository. >> [Posiva]

- << The statement of “not imposing undue burdens on future generations” implies that the long-term safety of such a facility shall not rely on human actions, such as an extended institutional control period. >> [FANC]
- << After closure of the repository, institutional controls remain in place for a limited period, amongst others to prevent intrusion into facilities, which is a particular concern for near surface repositories. As such controls cannot be maintained forever, additional measures have to be taken in order to limit the likelihood and the radiological consequences of human intrusion (HI) after the end of the institutional control period. >> [FANC]

Outcome of the workshop:

Although this issue was addressed at the workshop the participants decided not to discuss institutional control in a detailed manner because this is primarily the task of the regulators to make decisions and to provide appropriate guidance. It was acknowledged that institutional control might be an effective measure against HI, at least in the short term after repository closure.

Information preservation:

The main intention of preserving information and taking precautionary measures to preserve the knowledge for future generations is to maintain the awareness of existing disposal sites and of the potential hazard posed by the respective repository. As a result, the risk of inadvertent intrusion into the disposal system can be excluded or at least reduced. Other intentions relate to the development of an information database that can serve for future generations as a sound basis for decision-making processes with respect to future uses of the site or in case of need to take suitable precautions and to plan the activities accordingly.

Information preservation is basically a passive control measure and involves the necessary condition for preventing inadvertent human intrusion. However, the sufficient condition is that the future generations keep aware of the preserved information and that they interpret them appropriately. The latter condition is often discussed in connection with active institutional control.

The topic of the preservation of information involves a wide spectrum of issues which were discussed on a national and international level at different occasions. These questions concern e. g. the kind, form and amount of information to be preserved, the choice of suitable data media and data management systems, the strategies for making future generations aware of the information and the financing options. These issues were not primary concern of the contributors and therefore they are not discussed any further. Other issues are of interest, like the required timeframe for information preservation and the assumption for the earliest possible time of HI in safety assessments after repository closure. The latter issue relates to the matter of how long people can rely upon information preservation as a measure for preventing HI.

Actually, both the required timeframe and the earliest possible intrusion time cannot be determined on a scientific basis and should be therefore fixed in regulations. A common approach is to equate the earliest possible intrusion time with the time of loss of information. The preservation of information on the other hand should be carried out as long as possible. Since this is an undefined specification, some countries take into account historical documents e.g. maintained by archives, registers or national libraries. The experience shows that information could be preserved for some hundreds of years. The following are some examples from the contributors that refer to the issue information preservation:

- << In these conditions, the loss of memory of the existence of the repository can be reasonably situated beyond 500 years. This value of 500 years will be retained as earlier date of occurrence of a human intervention. >> [Andra]
- << In case of inadvertent human actions the knowledge of the repository has to be lost at the time of occurrence. Thus, such kinds of scenarios are assumed to occur not before several 100 years after repository closure. Within the ERAM study human intrusion after 500 years has been assumed and in PAGIS and EVEREST 1000 years have been regarded as reference values >> [GRS-BS]
- << It is assumed that for the treatment of the scenarios, which describe the inadvertent human intrusion, the knowledge about the repository remains at least 500 years. Therefore, no earlier point in time for the intrusion scenario needs to be chosen. >> [GRS-K]
- << Therefore in the dose calculations for these scenarios it was assumed that this kind of action would not take place earlier than 250 years after discharge of the reactor fuel to be reprocessed. >> [NRG]
- << Information of the repository and the waste is stored in several archives. Storing of the information and markers, which might be constructed at the disposal site, are currently being studied in co-operation by the Nordic countries as well as in a wider international context. >> [Posiva]

Outcome of the workshop:

It is obvious that information preservation cannot last for eternity. However, experience shows that information could be preserved for some hundreds of years but this time span is only marginal compared to the considered isolation period. However, there was a general consensus that like the depth of the repository, the preservation of information and the maintenance of knowledge is one of the most appropriate measures against HI. It is expected by the majority of participants that specific guidance in this matter should be provided by the regulator.

Other measures like marker, making access difficult etc.:

- In addition to the measures discussed above there are some other possible measures like markers and monuments which could act as passive institutional controls. Further options include design measures that shall increase the resistance against HI actions e.g. an increased wall thickness of waste casks as a barrier against drill bits. The following are some examples from international organisations and participating organisations which address further measures like markers and make it difficult to intrude:

<< ...incorporating robust design features which make intrusion more difficult, or employing active institutional controls (such as restricting access or monitoring for potential releases) and passive institutional controls (such as records and markers). >> [ICRP, 1998]

- << At somewhat greater times, large-scale physical markers at or near the site may help reduce the likelihood of disruptive human actions. Recent work in the U.S. suggests that well designed markers have a high likelihood of maintaining their effectiveness for periods on the order of several thousands of years. On the other hand, some argue that far in the future the message concerning the hazard associated with the repository might not be properly understood, and that markers may serve primarily to increase interest in the repository. In any case, surface-based marker systems located in areas prone to glaciation are unlikely to survive such glaciations when they next occur (on the order of 10,000 years from now). >> [NEA, 1995]
- << Physical barriers to intrusion (e.g., a thick concrete Cover above the disposed waste or a strong canister) may lower the probability of inadvertent intrusion. However, this is probably the least effective countermeasure, and is not discussed further. >> [NEA, 1995]
- << [NAS, 1995] concludes that we can not rely on passive control (markers and archival of records) to ensure that no human intrusion takes place because „there is no technical basis for making forecasts about the reliability of such passive institutional controls". >> (Enresa follows the recommendations of NAS) [Enresa]
- << Complementary means, independent from the characteristics of the system, may also contribute to reduce the likelihood of a HI event. These means are aimed to make the intruder conscious of the presence of the repository and of the radiological and non-radiological risks that it represents. >> [FANC]

Examples of complementary means are ensuring the long-term conservation of the memory of the repository, physical markers and land-use restrictions.

- << ...the possibility of implementing complementary measures for limiting the dispersion of radionuclides following a HI event (using for instance intermediate sealing plugs) and for increasing the resistance of the system against intrusion should be investigated. >> [FANC]
- << An aboveground marking of the repository is not required in terms of the routinely environmental protection measurements and topographic measurements. >> (according to the regulations "Safety Criteria" from [BMI, 1983]) [GRS-K]
- << The use of site markers and archives to increase the probability that information about the site is retained for as long as possible >> [NDA]
- << ...to demonstrate that all practicable steps to record information about the facility have been taken. This might include: The provision of durable site markers ...>> [NDA]
- << Storing of the information and markers, which might be constructed at the disposal site, are currently being studied in co-operation by the Nordic countries as well as in a wider international context. >> [Posiva]

Outcome of the workshop:

It was decided at the workshop that the participants will not formulate a joint statement on the issue of markers and other additional measures besides those which are discussed above. During the discussion it was recognised that there is a wide spectrum of opinions regarding markers which include the pros and cons in terms of preventing HI. The given examples from international references and contributors demonstrate this. However, it was again agreed that this issue is also a subject for the regulators.

9.4.5 Types of HI actions and scenarios

This subchapter describes different human actions which constitute the initial basis for HI scenarios. It also considers motivations and different purposes for those human actions.

The following gives several examples for HI events/ scenarios from the contributors which were developed and in some cases have been used in safety assessments:

- << ... scenarios are drilling for water, exploratory drilling with the extraction of core, operation of a mine near the repository or direct physical human intrusion into the disposal facility. >> [FANC]
- << ...the following sources for “Human Intrusion“ into a deep geological repository have to be discussed depending on respective site conditions: exploratory drilling, construction of a mine, extraction of geothermal energy and utilisation as reservoir rock (pore-space store, cavern) >> [GRS-K].
- << According to a guide from the regulatory body ASN in France [ASN, 2008], several specific altered situations connected to human activities were definedAndra:
- exploratory drilling crossing a repository structure,
- abandoned and badly sealed exploratory drilling crossing a repository structure,
- drilling in a deep aquifer for exploitation of water destined to food or agricultural usage [Andra] >>.
- In accordance with the regulations, human intrusion was dealt with an immediate impact situation (from operating borehole cores) and a differed impact situation. This last situation includes several cases resulting from abandonment of boreholes in various location of the repository (drifts, disposal cells, or in the packages). In order to mobilize the maximum radiological inventory it was presumed that the event took place after exactly 500 years [Andra].
- << In this HI scenario it is assumed that 500 years after repository closure, when the institutional control period has passed there are mining activities in the area of the repository. An exploratory borehole intersects vertically a disposal canister, and the drilling head cuts pieces of the spent fuel disposed in the canister and significant amounts of radionuclides are released from the waste. Most of the contaminants will be extracted in the core or the drilling slurries sent to the slurry pool in the surface. The rest of the radionuclides released will remain sorbed on the surface of the borehole or will dissolve in the groundwater. After the drilling the borehole is left unsealed, and since that

instant radionuclides in the borehole column can be transported by groundwater. >> [Enresa]

- << In the selected HI scenario, the radiological consequences of the exploratory borehole on people who perform the drilling or inspect the cores are not analysed. The long term consequences of the pool of slurries are not considered either. The objective of the scenario is to analyse the effects of the intrusion on the isolation capability of both the engineered and natural barriers. The borehole damages the engineered barriers (canister and bentonite) of the intersected canister. In addition, since water travel time usually increases with depth, the radionuclides deposited in the borehole column will reach the Biosphere faster than the radionuclides released at repository depth. >> [Enresa]
- << Inadvertent human intrusion scenarios are mainly possible in the scope of exploration or mining activities of future generations. ... These are borehole drilling, constructions of a mine, and cavern leaching. >> [GRS-BS]
- According to [GRS-BS], a general evaluation of the issue human intrusion has been performed on behalf of the Federal radiation protection office (BfS). In the framework of this evaluation the following six human intrusion scenarios were investigated to different host rocks:
  - mining into the contaminated host rock region, drilling into a waste container,
  - drilling into a waste container
  - drilling into the repository without hitting any waste
  - opening up of an underlying groundwater reservoir under overpressure by drilling
  - opening up of a contaminated aquifer by drilling and
  - solution mining of evaporite rocks.
- << Possible inadvertent acts of human intrusion include drilling or excavation into the repository or the surrounding rocks, for the purpose of exploring for or exploiting natural resources (e.g. coal, oil, gas or minerals). >> [NDA]
- << Human intrusion is considered in guide reports ... Specifically, drilling activities are mentioned. >> [NRI]
- In case of [NRG] a FEP list of numerous human induced phenomena was taken into account. The FEPs of human induced phenomena were divided into two classes:
  - post-closure and sub-surface activities;
  - post-closure and surface activities.
- The analysis of the FEPs led to the following human intrusion scenarios which were subject of safety assessments [NRG]:
  - leaky storage cavern,
  - reconnaissance drilling
  - solution mining and
  - conventional mining.
- Finish regulations [STUK, 2001] state that human intrusion scenarios should include
  - boring a deep water well at the disposal site and
  - core-drilling hitting a waste canister.

- << Postulated possible scenarios, taking the regional context into account, are drilling for water, exploratory drilling with the extraction of cores, the operation of a mine near the repository or direct physical human intrusion into the disposal facility. >> [SCK/CEN, ONDRAF/NIRAS]
- << It is now planned to develop a number of unsealed borehole scenarios and to evaluate the radiological consequences resulting from these scenarios. >> [SCK/CEN, ONDRAF/NIRAS]

Although the HI actions/ scenarios by the different contributors differ according to their requirements, the range of initiating events is limited. Hence, the HI actions/ scenarios were developed primarily on the basis of drilling and mining activities. The range of envisaged reasons and techniques is also restricted, but include:

- drilling and operation of a borehole
    - exploration,
    - exploitation of resources e.g. oil, gas, minerals,
    - extraction e.g. of groundwater, geothermal energy
    - injection e.g. liquids and gases
- construction and operation of a mine at the site or in the vicinity
    - excavation, solution
    - solution mining e.g. minerals,
    - conventional mining e.g. coal, ores, other minerals
    - utilisation e.g. storage and disposal of substances
- construction and operation of a cavern
    - excavation, solution
    - leaching e.g. salt
    - utilisation e.g. storage and disposal of liquids and gases

From the examples above, only Enresa has described a HI scenario “exploratory borehole” which includes all the elementary data for the investigation. It should be also noted that in this HI scenario the borehole is left unsealed after the drilling. Some other organisations, like Andra, mentioned similar situations of badly sealed exploratory boreholes.

Outcome of the workshop:

With regards to events, techniques and reasons which form the HI scenarios the participants concluded:

The main sources for HI events are drilling and mining, whereas the main purposes are exploration of the site, exploitation and extraction of natural resources and injection of substances and/ or resources for storage and disposal. These topics take into account the assumption that HI should be considered in the view of today´s available technology and habits of the society. It was also concluded that exploratory drilling is actually the initial event for all the other actions like mining and exploitation.

9.4.6 Anomalies and noticeable features

At the end of construction, disposal systems in deep geological formations might leave no visible footprint at the surface, but may leave underground traces including unnatural, abnormal or unexpected environmental features. Some indications of the existence of waste and repository characteristics are:

- Differences of porosity, permeability and density in consequence of mining activities and backfilling of e.g. bentonite, crushed salt.
- Differences in temperature of such disposal areas caused by heat generating wastes.
- Emplacement of dissimilar material into the underground such as waste containers, canisters, casings, concrete, radioactive waste etc.
- Ionising radiation, radiotoxicity

In relation to this the question arises whether there is potential for the detection of such anomalies in connection with human actions, e.g. by accompanying measurements during exploratory drillings and other activities. Therefore, specific investigations can give information whether future generations should be wary about the existence of an underground construction and/ or the associated hazard before, during and after their site activities. Results of the investigations might deliver additional arguments for the evaluation of HI in the safety case.

There are only few examples from the contributors that discuss the possible detection of the disposal system and the associated hazard:

- << Deep boreholes and shafts are not made arbitrarily in common rock types, but drillings and excavations are preceded by airborne and ground-based geophysical investigations, by which the repository will be detected. [Vieno, 1992] >> [Posiva]
- << The construction of a repository in deep geological formations ... indicate abnormal or unexpected environmental properties. ... In this connection the question arises of detection potentials of anomalies through exploratory drillings and other activities. The investigation of such detection potentials should be also one of the different tasks in analysing the provided reference scenarios. >> [GRS-K]
- << For the core inspection scenario it is proposed to assume that the presence of the thick metallic overpack will make an inadvertent intrusion into the disposed waste unlikely during several thousands of years. Also for the dispersal of radioactive materials it can be expected that during long time spans the drilling team should become aware of the presence of exotic materials in the cuttings and that they should take protective measures. >> [SCK/CEN, ONDRAF/NIRAS]
- The intrusion could first of all be the result of detection of the fact that there is a particular object in the ground and the desire to find out what it is. The disposal could in theory represent a geophysical « anomaly » that can be detected from the surface: a magnetic anomaly owing to the presence of metal materials in the repository, a gravity anomaly owing to the materials density different from that of the geological medium. The studies performed by Andra show that only a 3D seismic investigation could detect the

anomaly caused by the repository. In terms of a gravity anomaly, the repository's visibility is very low as the densities of the various materials on the whole compensate for each other. The repository may also have been detected from the surface: excavations bringing to light traces of former surface installations or old access structures. In such a case, an « archaeologist » might attempt a reconnaissance of the structure. Good practice would require that he begins by looking for the origin of his discoveries in the archives, where he could then identify that he had found a radioactive waste repository [Andra].

Outcome of the workshop:

The investigation of HI scenarios should also include discussion of whether the anomalies induced by the waste and the repository could be detected based on today´s knowledge and applied technology.

9.4.7 Exposed groups, doses and risks and evaluation of consequences

This section considers the different aspects of HI scenarios with regards to the calculated doses resulting from assessments. This encompasses the exposed groups of people, evaluation of consequences and risks, applied dose limits, exposure paths and appraisal of results.

The underlying questions here relate to the general objectives for the analysis of HI scenarios, and if dose calculations are required, how and where are doses included in the evaluation of safety.

Exposed groups of people:

For most of the contributors the groups of people that should be considered for HI scenarios are groups of intruders and/ or a group of residents. Some consider a reference group which can be a group of the surrounding population [FANC]. For Enresa the receptor in the HI scenarios is the same average member of a critical group considered in the reference scenario.

Another feature was the distinction between direct and indirect contact with the waste for the two groups as a consequence of HI [SCK/CEN, ONDRAF/NIRAS]. A direct contact with the waste, e.g. as a result from contaminated material brought to the surface, is assumed to occur to both the group of intruders and the resident group. Indirect contact is assumed to occur only to the resident group that, for example, assimilate contaminated groundwater.

Two types of situation were also examined by Andra:

- Situations resulting from the resurfacing of cores, debris, or cuttings and contaminated rock from a borehole. In these situations the radiological impact is immediate. Waste first give rise to an exposure by external irradiation, of one or more of the workers causing the intrusion.
- Situations resulting from the abandonment of one or more boreholes. Such situations, in which the potential radiological impact is deferred, bring to the biosphere part of the

radionuclides initially contained in waste and which have migrated from the package through the borehole. The persons potentially exposed in the medium or long term are assimilated with individuals belonging to a hypothetical critical group.

Doses and risk:

There is a broad consensus that HI scenarios can lead to high doses particularly for the group of intruders. Some contributors point out that the comparison of calculated doses for the group of intruders with regulatory limits or the considerations of such cases is not appropriate. Concerning risk, it is also mentioned in one case that due to the expected extremely low occurrence probability of HI the resulting risk is acceptable. The following are excerpts from international references and from the contributors which relate to these considerations:

- << In the event of inadvertent human intrusion into a geological disposal facility, a small number of individuals involved in activities such as drilling or mining into the facility could receive high radiation doses. >> [IAEA, 2006]
- << Whenever highly dangerous materials are gathered into one location and an intruder inadvertently breaks in, that intruder runs an inevitable risk. >> [NAS, 1995]
- << ...it does not make really sense to consider the case of the intruder himself, as the level of doses received by a non-protected person coming into direct contact with the waste will surely be lethal. >> [FANC]
- << ...the probability of occurrence of a HI event could be considered as extremely low (and thus the resulting risk acceptable)... >> [FANC]
- << Inadvertent human intrusion scenarios, if they occur, can lead to very high doses ... >> [NDA]
- << ... doses received by the intruders can be high and it would be difficult to reduce them by the repository design. However, these high doses are closely linked to the "concentrate and contain" strategy and, consequently, comparison with a regulatory limit is not considered relevant. >> [SCK/CEN, ONDRAF/NIRAS]

Dose limits

A comparison of calculated doses with thresholds calls for regulations that provide respective dose limits. In this context, since the receptor is the same than in the reference scenario, Enresa uses the same dose limit of 10^{-4} Sv/yr for the HI scenario, even though there are no specific regulatory requirements or guidelines.

Exposure paths:

It was suggested that the exposure of people from external irradiation, inhalation of radionuclides and ingestion as a consequence of drilling activities should be evaluated [NRI].

Evaluation of consequences:

There are references from international organisations [IAEA, 2006], [ICRP, 1998] which recommend that calculated doses from HI scenarios should not be compared with doses and risks but the resilience of the disposal system to such events should be evaluated. Similarly, [NAS, 1995] and [FANC] recommended appraisal of the robustness of the disposal system in terms of HI. Others indicate that quantitative assessments are practically impossible and suggest therefore the interpretation of HI scenarios as rest risks [Posiva].

Outcome of the workshop:

Taken into account the discussion above the participants concluded the following:

There are actually two types of exposed groups in the case of HI events:

- Group of intruders which might receive immediate or direct consequences;
- Group of people (residents, public) which might receive direct and indirect consequences).

Due to the widely varying underlying assumptions for HI scenarios, the radiological consequences vary greatly.

The investigation of HI scenarios should be undertaken in a more qualitative manner. The participants held the view that calculated doses should not be measured against radiological thresholds. However, they acknowledged that there might be some cases that allow the developer to treat the HI scenario like a common alternative scenario, e.g. release of radionuclide via groundwater path.

Finally, it was stated that the consequences should be more seen as indicators which give information about the resilience and robustness of the disposal system.

9.5 Application and Experience

The following examples show that the participating organisations have gained a lot of experience in dealing with the subject of HI. In fact, a wide range of applications and reasons are in evidence. This includes the practice in safety analysis, performance assessment exercises, licence applications and review processes. Few contributors thought the participation in the program was not helpful.

The range of HI scenarios considered is rather limited as indicated in section 9.4.5 and can be mainly attributed to borehole drilling, mining activities and construction of a cavern. It is also noted that borehole drilling is the basis accounts for a HI scenario for almost all contributors.

- << In the framework of the Dossier 2005 Argile, the description of the Human Intrusion was defined as a “Borehole scenario” [vii]. This document describes some consequences of the creation of a borehole in the repository, particularly in coherence with regulations (RFS.III.2.f [i] of 1991). Quantification of such an activity is discussed in the Assessment of Geological Repository Safety Report [vii]. >> [Andra]

- << Enresa has considered human intrusion only in one of the PA exercises carried out for a repository in granite. On the basis of the FEP analysis, a human intrusion scenario (exploratory drill) is identified, defined in detail, and a consequence analysis of such scenario carried out. >> [Enresa]
- << Human intrusion scenarios have been applied in the safety assessment studies for high-level waste PAGIS and EVEREST and in the framework of licensing applications for real repositories with intermediate and low level waste in Morsleben. >> [GRS-BS]
- << There is experience with treating human intrusion scenarios for near surface repositories... No evaluation of human intrusion has been performed for deep geological repository. >> [NRI]
- << In [PROSA, 1993] four different scenarios were studied in an attempt to assess the potential radiological effects of human intrusion into a repository. Although these four scenarios do not deal exhaustively with the potential consequences of human intrusion, they seem adequate for obtaining an idea of the similarities and differences between disposal concepts (with respect to the consequences of human intrusion). >> [NRG]
- << The extended PROSA method [12] has been applied for the safety study supporting the license application for the closure of the Asse (D) salt mine including the experimental disposal facilities (29. January 2007 [13]) and for a review on behalf of the Ministry of Agriculture and Environment of Sachsen-Anhalt (MLU) of two supporting reports issued in 2002 in preparation of the licensing process for the Morsleben Repository for radioactive waste (Endlager für radioaktive Abfälle Morsleben - ERAM) [14]. >> [NRG]
- << Calculation cases for the human intrusion scenario have not been developed since the TVO 85 Safety analysis [Vieno, 1985]. No new analyses on human intrusion were considered necessary for later safety analysis TILA-96 or TILA-99. >> [Posiva]
- << The experience on the treatment of human intrusion scenarios in Belgium is rather limited because the interaction between the waste agency and the radiological protection authority has not yet started for safety cases for geological disposal ... >> [SCK/CEN, ONDRAF/NIRAS]

The participating organisations have gained a lot of experience in dealing with HI. As a result, every participating organisation has learnt their own lessons, which can be valuable for all readers. Some of which include:

- The analysis of a borehole scenario with different considered situations has revealed that the disposal system reacts in a robust way [Andra].
- A close collaboration between the implementers and regulators regarding the treatment of HI is recommended [Enresa], [SCK/CEN, ONDRAF/NIRAS].
- The potential of HI does not lead to a preferred disposal technique [NRG].
- Due to the potential of high exposures, HI scenarios should be the subject of further studies [NRG].
- The treatment of HI has changed drastically from the consideration of pure disruptive scenarios to more realistic events [SCK/CEN, ONDRAF/NIRAS].

Finally, it has to be stated, that we can learn a lot from each other and should learn from the experiences of our partners abroad, both in a positive and negative sense.

9.6 Developments

Developments in HI are mostly due to experience gained from previous work, lessons learnt, reviews or revised conditions and frameworks. In this document a broad variety of developments and future work from the developers is in evidence. Some are planning to re-examine HI scenarios [Andra] or extend existing methods [NRG] while others currently do not have specific work on HI but will start to consider it in the near future [NRI] or will follow international developments [Enresa]. Others will develop stylised HI scenarios in clay [SCK/CEN, ONDRAF/NIRAS] or will formulate calculation cases for HI by the end of 2010 [Posiva].

Regarding regulatory developments, it was mentioned that the recently revised regulatory guidance in the UK now places a greater emphasis on presenting assessments of doses to individuals representative of those undertaking the intrusion and to those who might occupy the area after and intrusion, rather than presenting the risk from HI [NDA]. Others refer to the recent initiation of the development of regulatory guides for geological disposal facilities [FANC] and the revision of existing regulations [GRS-K]. There is also the envisaged interaction between the regulatory authority and the waste management organisation in Belgium on safety cases for geological disposal by the end of 2009 [SCK/CEN, ONDRAF/NIRAS].

Some work from a regulatory view will be done in the frame of WP 3.1 of the PAMINA project regarding the development of stylised HI scenarios in salt [GRS-BS], [GRS-K].

Further developments from the implementers are:

- << In line with the new 2006 French Act and the 2008 revised version of the safety rules [ASN, 2008], the scenario “borehole” will be re-examined taking account of design optimisation and knowledge acquisition (including new data on the site of Meuse Haute-Marne). >> [Andra]
- << Enresa is making no in-house developments on this topic, but international developments are followed. >> [Enresa]
- << Currently an evaluation is performed lead managed by GRS-K to work out a joint view, how to treat human intrusion scenarios in a German safety case. >> [GRS-BS]
- << ...the revised regulatory guidance has an updated section on human intrusion, which places a greater emphasis on presenting assessments of the doses should human intrusion take place, rather than on the risk, which includes an estimate of the likelihood. >> [NDA]
- << No specific decision has been accepted so far for treating human intrusion scenarios in next performance assessments of DGR in the Czech Republic, but discussion on this issue will start this year in the framework of RAWRA project focused on update of reference design DGR from 1999. >> [NRI]

- << We expect that the PROSA procedure for identifying scenarios will be extended by the application of 'safety functions' for future safety studies. >> [NRG]
- << Currently there is not ongoing work on human intrusion scenarios, but measures to diminish the likelihood are being taken [Saanio, 2006]. The formulation of calculation cases for this kind of scenario are to be planned by the year 2010, well in time for the application of construction permit in 2012. >> [Posiva]
- << Within the framework of PAMINA work package 3.1 SCK/CEN has developed a number of stylised human intrusion scenarios that are relevant for geological disposal in clay formations. >> [SCK/CEN, ONDRAF/NIRAS]
- << ... the interaction between the radiological protection authority FANC/AFCN and the waste management agency ONDRAF/NIRAS on safety cases for geological disposal will start during the last months of 2009. >> [SCK/CEN, ONDRAF/NIRAS]

Developments from the perspective of the evaluators are:

- << FANC recently initiated the development of regulatory guides for geological disposal facilities. The implications of the high-level requirements developed in this framework on the treatment of human intrusion were also considered in the discussions and positions presented in this paper. >> [FANC]

Existing suggestions and draft reports that include new and revised requirements are currently under discussion. These documents serve as a basis for the intended replacement of the current legal regulations “Safety Criteria“ from 1983 [BMI, 1983] [GRS-K].

In addition, HI activities and their possible implications have been discussed in the German Working Group on “Scenario Development”. As a result, the Working Group prepared a joint position that contains recommendations how to deal with “Human Intrusion” in the safety case. This joint position served as a basis for the development of stylised HI scenarios in salt from a regulatory perspective in the framework of WP 3.1 of PAMINA project [GRS-K].

9.7 Conclusions

The topic "Human Intrusion" (HI) is one of many other topics which have been addressed within the framework of RTDC-1 of the integrated project PAMINA. Chapter 9 summarises the main facts, aspects, and views regarding HI on the basis of contributions provided from participating organisations, international references as well as selected national reports from countries with advanced disposal programmes. In addition, a number of specific aspects of HI were discussed at a workshop, taking into account the above points. The outcome of the workshop provides a set of common opinions with only a few reservations from participants. There is a good degree of consistency amongst contributors on the subject of HI.

The main results of the topic HI can be summarised as follows:

Regulations:

There are different positions concerning the regulatory aspects of HI in the various countries. Some countries have established regulations, others currently work on specific regulations or revise existing ones, and others in turn do not have any regulations at all. However, there is a broad consensus about the strong need of regulations for the treatment of HI in the safety case. In terms of regulatory requirements the workshop concluded that:

The treatment of HI should be addressed in regulations and guidelines provided by the respective responsible authorities. Regulations and guidelines should include e.g. the framework for the analysis of HI scenarios, scope of the investigations, constraints and conditions. In addition, the scenarios should be determined on a stylised basis, since a systematic development of HI is not possible. However, it should be acknowledged that stylised HI scenarios can never be complete or comprehensive. Furthermore, the topic of HI should be already considered in the site selection process and in the design phase of a repository.

Terminology:

There are few definitions from the contributors. Some contributors explicitly defined the term HI, but the definitions are rather different in terms of the wording. However, they do share the view that human intrusion involves a direct damaging of the barriers.

As a result of the workshop the participants agreed that “HI can be understood as human actions which have the potential to directly jeopardise the isolating capacity of the barriers of the disposal system and therefore might have radiological consequences. Other terms associated with HI like unintended actions will be accepted according to provided definitions from the OECD/NEA. Another agreement relates to stylisation of HI scenarios”.

Methodology:

This issue comprises a number of aspects for the treatment of HI from both the view of the developer and the evaluator. The main observations from the contributors and from the discussion at the workshop can be summarised as follows:

- Human actions over timescales which are relevant or of interest for the disposal of high active waste are unpredictable. In addition, it is not possible to derive HI scenarios in a systematic way like for the other scenarios. The same applies to the derivation of the occurrence probabilities for HI events. As a consequence, the HI scenarios should be determined on a stylised basis whereas current technology and social behaviour have to be taken into account. Furthermore, only unintentional human intrusion should be considered. Intentional human intrusion, i.e. human actions with knowledge of the disposal site and the hazardous waste, are the responsibility of the society taking that action.
- It was agreed that HI is a major concern when discussing safety of the disposal system. However, there are different opinions about where and how HI has to be treated in the safety case. It was the majority view that this depends on the respective conditions and regulations in the different countries, but if HI scenarios are examined then the effectiveness of specific measures has to be evaluated. Although HI cannot be

predicted, the consideration of appropriate measures against HI is limited, but a sufficient depth of the repository and information preservation, are considered as the most appropriate measures against HI. There is general agreement that measures themselves must not compromise other safety aspects of the repository.

- It was also agreed that sites with valuable resources should be avoided in the site selection process in order to reduce the likelihood of HI as much as possible. There are some reservations as to whether the likelihood can be really reduced over the long timeframes that are considered in safety assessments. Other measures like institutional control and markers were not discussed in detail because these issues should be part of regulations and guidelines.
- In terms of the types of HI action, the participants hold the view that the main type of action is drilling and mining associated with exploration of the site, exploitation and extraction of natural resources and injection of substances and/ or resources for storage and disposal. It was concluded that exploratory drilling is actually the initial event for all the other actions like mining and exploitation.
- Finally, it was agreed that the investigation of HI scenarios should also consider if the anomalies induced by the waste and the repository could be detected based on today´s knowledge and applied technology.

Application and experience:

A wide variety of applications and purposes were noted amongst contributors. This includes the practice in safety analysis, performance assessment exercises, licence applications and review processes. Again, it was apparent obvious that the close cooperation between evaluators and developers on the treatment of HI in safety assessments and the safety case is needed.

Developments:

Again a broad range of developments and future work from the developers is being carried out. Some are planning to re-examine HI scenarios or extend existing methods while others currently do not have specific work on HI but will start discussion soon or will follow international developments. Others will develop stylised HI scenarios in clay and salt or will formulate calculation cases for HI.

9.8 References

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10. Biosphere

10.1 Introduction

Geological disposal of long-lived radioactive waste is being widely investigated as a means of protecting people and the environment from the waste for as long as it remains hazardous. A geological disposal facility may be considered safe if it meets the relevant safety standards that are internationally recommended and those specified by the national regulator.

The radiological hazard posed by the disposal facility is one of the safety criteria upon which the overall long-term safety of the disposal is assessed. The radiological consequences of disposal will arise in the "biosphere", should there be any release from the engineered and natural barriers of the disposal system. The International Atomic Energy Agency [IAEA, 2007] defines the biosphere as *"that part of the environment normally inhabited by living organisms"*. The biosphere can thus be considered as the environment or system in which radiation exposures can occur. The aim of biosphere modelling is to convert concentration or the flux of activity reaching the environment into a dose incurred by a member of a hypothetical critical group or by the group. Thus it provides an indicator of the radiological impact associated to a potential geological repository. The many uncertainties related to biosphere evolution in time and the ensuing difficulties to define hypothetical critical groups, lead to acknowledge that several different modelling assumptions are reasonably thinkable and that each can possibly result in a different calculated dose.

This chapter collates the views from European organisations participating in the PAMINA Project on their treatment of biosphere issues in safety assessments for geological disposal of radioactive waste. The key issues summarised in this chapter include the concept of the biosphere and its description in safety assessments, the various interpretations of dose criteria, and the models used for dose conversion in relation to radionuclide releases from the geosphere.

10.2 Regulatory Requirements and Guidance

The radiological hazard due to the disposal facilities can be measured in terms of the risk to individuals. The International Commission on Radiological Protection (ICRP) describes *radiological risk* in terms of the radiation dose received during exposure (Sv) [ICRP, 1998]. It also publishes conversion factors for the effective dose (Sv) corresponding to a certain exposure (in Bq). Safety assessments must therefore consider radionuclide transfer rates and environmental concentrations in the biosphere, and how these can be transformed into a measure comparable to applicable health standards. Current guidance from the ICRP suggests a value of 0.073 Sv^{-1} as the risk coefficient, i.e. conversion factor for exposure to ionising radiation [ICRP, 1990]. This gives the risk of an exposed individual dying from radiation-induced cancer, and includes potential genetic effects in subsequent generations. The level of risk to the individual that society tolerates can be expressed in terms of an annual individual dose received by potentially affected individuals. In Europe, Euratom Directive 96/29 [Euratom, 1996] gives appropriate dose limits for several exposure scenarios.

For members of the general public, a dose limit of 1 mSv/year is cited, in accordance with the IAEA's advice on the safety requirements for geological disposal [IAEA, 2006]. Interpretation of this value for radioactive waste disposal facilities provides the basis for regulation at the national level, as discussed below. The more advanced national regulatory frameworks complement fundamental dose or risk limits with safety requirements that aim to reinforce the demonstration of safety by suitable arguments and analyses in the safety case. It should also be noted that guidance is evolving in several countries.

Belgium: The Belgian regulator (FANC) has recently issued guidance on the management of licence applications, which contains safety principles that apply to any disposal facility for radioactive waste in Belgium [FANC, 2007]. The FANC is currently developing detailed guidance for near-surface disposal facilities that will be issued in the next two years. The development of more detailed regulatory guidance for geological disposal facilities for high-level waste is also planned, and will be based in large part on the guidance developed for near-surface disposal facilities. Current regulatory guidance includes five "expectations", setting aspects of the biosphere that should be explicitly addressed:

- For each important biosphere receptor, a critical group or a potentially exposed group and the reference organisms shall be determined,
- For each critical or potentially exposed group, all transfer pathways and exposure pathways shall be identified,
- Regarding reference organisms, the state-of-the-art of international developments shall regularly be checked,
- All receptors, transfer pathways and exposure pathways shall be taken into account in such a way that the radiological impact will not be underestimated,
- Various timescales should be considered.

Czech Republic: In the Czech Republic, the State Office for Nuclear Safety (SÚJB/SONS) is responsible for the licensing of a geological disposal facility. Reasonable assurance must be provided in the safety case that doses to members of the public in the long term will not exceed 0.25 mSv/year for normal evolution of the facility under consideration [SÚJB, 2002]. A higher dose limit (up to 1 mSv/year) is applicable for lower probability scenarios.

Finland: Finnish waste disposal programme is at an relatively advanced stage, and regulatory requirements for the disposal of spent nuclear fuel are well developed, following the recommendations in the Council of State Decision (478/1999) of 25 March 1999. The Decision places conditions on the geological characteristics of the site, the disposal facility depth, the nature of the barriers, and the implementation and timing of disposal. Also, criteria on long-term radiological protection performance are specified for the disposal system, in terms of dose to humans and release rates of long-lived radionuclides from the geosphere into the biosphere [STUK, 2001]. The dose constraint is 0.1 mSv/year for the most exposed members of the public. In addition, the exposure should be "insignificantly low" for the other people, – more specifically doses must not exceed 0.001 to 0.01 mSv/year, where the applicable dose constraint depends on the size of the exposed group. Consideration must also be given to protect other living species and, although no numerical dose constraint is stated, any exposures should remain below the levels that would affect detrimentally to species of fauna and flora on the basis of the best available scientific knowledge. It is recognised, however, that applicable methods for estimating such exposures are still under development internationally, and they may need to be implemented more explicitly within the regulatory framework at a later date.

Some guidance is also provided in Finland on potential exposure environments and exposure pathways. According to [STUK, 2001], the most exposed individuals should be assumed to live in a self-sustaining family or small village community in the vicinity of the disposal site, at the point where the highest radiation exposure is expected to arise. The community is assumed to be located near a small lake and a shallow water well. Other members of the general public are assumed to live at a regional lake or at a coastal site and to be exposed to the radionuclides transported in these watercourses.

France: The current regulatory framework is based on a guidance initially published by the Nuclear Safety Authority (ASN) in June 1991, the Basic Safety Rule n°III.2.f (RFSIII.2.f) newly released in 2008 [ASN, 2008] (called below “the guidance”) in order to introduce notions and safety approaches developed in the “Dossier 2005 Argile” edited by Andra and to take into account for the Planning Act n°2006-739 of 28 June 2006. A dose limit for individuals of 0.25 mSv/year is applicable for a reference scenario. This value is set at a quarter of the limit for the general public to take account of exposure by different practices over the period of the assessment. The guidance also provides rules and definitions on aspects of the biosphere.

To verify that the radiological protection objectives of the repository are reached, the post-closure safety assessment must cover the future behaviour of the repository and check that individual exposure is acceptable. The approach adopted shall consist in considering a limited number of situations representative of the different families of events or sequences of events such that the associated consequences are the greatest among those of the situations of the same family. The families of events or sequences of events adopted shall be those considered to be conceivable among all those which are a priori possible, considering the expected performances of each component and the disturbances caused by the creation of the repository. It is recommended that the data used in the models should be either pessimistic to overestimate the radiological impact, or best-estimate data associated with sensitivity analysis for exploring their possible variation.

The guidance indicates that the Biosphere is the part of the Environment easily accessible to the activities of human kind and prone to be a transfer way of radioactivity involving an internal exposure (inhalation, ingestion) or an external exposure. The biosphere may include:

- The aquifers used for water consumption,
- The outlet zone of the groundwater that could be affected by the repository,
- The superficial discharge system of these groundwater,
- The soils that could be affected by irrigation or flooding by the previous water system,
- The agricultural or animal production able to be used for human consumption,

- The surrounding atmosphere.

The guidance also indicates that in the biosphere it seems not possible to predict the local evolution of the environment for long time periods; on the other hand, the large climatic events that are predictable at a regional level should be taken into consideration by developing *"biosphere types"*. Concerning the exposed group, the guidance rules, that radiological impact must be calculated for reference hypothetic groups, which are representative of the individuals that could receive the highest doses and who are partially or totally living in autarky.

Germany: The guideline 'safety criteria for the final disposal of radioactive wastes in a mine' from 1983 [BMI, 1983] requires that the limit for the effective dose to an individual is 0.3 mSv/a given in the German Radiation Protection Ordinance. According to the current radiation protection ordinance, dose calculations have to be performed for six different age groups to ensure compliance for all population groups. Furthermore, organ doses have to be calculated and compliance has to be shown with organ-specific dose limits. For radionuclides, which accumulate preferably in specific organs, the organ dose might be the limiting value.

The German regulatory framework dates back to 1983, but GRS-K recently proposed a revision [Baltes, 2007], which is currently being considered by the advisory bodies to the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). The revision concerns the lowering of the 1983 annual effective individual dose limit, from 0.3 mSv/year to 0.1 mSv/year. Additional guidance is given in terms of what should be calculated over different periods in the future. It is felt that it is not possible to predict the development of the environment at the site for more than about 1,000 years. Therefore, only during this first period of 1,000 years dose calculations for a group of about 30 people of all ages are assumed to be reasonable. Beyond this time, the calculated "dose" transforms into an indicator of the disposal system's containment function and therefore consequence analysis will employ a "standardised climate depending biosphere models" with only adult males in the exposed group. The proposed size of the exposed group should consist of about 30 people. Additional guidance for the first 1,000-year period on the constitution of the biosphere models, for example food production will be elaborated in the future.

Netherlands: In the Netherlands, the safety assessment must demonstrate that individual risks and doses are below the regulatory limits, corresponding to 0.1 mSv/year. There are no further regulations relating to the biosphere. However, it should be noted that any licence application must also include an Environmental Impact Statement (EIS), which addresses, amongst other things, the ICRP principles for radiation protection, namely justification, optimisation, and compliance with dose limits. The EIS can use the safety report to show compliance with the ICRP principles.

Spain: In Spain, the Nuclear Safety Council (CSN) in 1987 established a regulatory safety criterion for the disposal of HLW radioactive waste in deep geological formations in terms of a maximum allowable individual risk of 10^{-6} y^{-1} or the equivalent in terms of maximum allowable dose of 0.1 mSv/y. There are no specific regulatory requirements or guidelines regarding the treatment of the Biosphere in the Safety Case.

United Kingdom: The UK regulatory framework is defined by the Radioactive Substances Act 1993 and the "Guidance on Requirements for Authorisation" (GRA), which outlines the safety principles and requirements that a developer of a disposal facility must meet. This guidance has recently been reissued [EA, 2009]. The GRA differentiates between the requirements for near-surface disposal facilities and geological disposal facilities, and introduces a staged authorisation process. For the post-authorisation period, the UK standard is expressed as an annual individual risk guidance level of 10^{-6} yr^{-1}. The UK environmental regulators recommend a detriment-adjusted risk coefficient for the whole population of 0.06 Sv^{-1}. An individual risk of 10^{-6} y^{-1} therefore translates to an individual dose of 0.02 mSv/year. During the period of authorisation, the environmental safety measure is a dose constraint of 0.3 mSv/year to a member of the critical group.

A range of dose limits is mentioned above, but only a few of the regulatory authorities have specified the "individual" for whom the annual individual dose (or risk) is to be calculated in the safety assessment. Similarly, the assessment timescales are generally undefined. Additional information is required to make use of the dose limits in safety assessments. The approaches taken are described in Sections 10.3 and 10.4 of this chapter.

10.3 Key Terms and Concepts

Regulations in the participating countries define radiological protection in terms of limits, or constraints on annual individual dose or risk. Some of the regulators also provide definitions of some of the key terms and concepts. However, for the most part, the task of deriving representative values of annual individual dose or risk in safety assessments requires that a substantial assessment database of biosphere concepts, FEPs (features, events and processes) and parameter values (including parameter distributions), be assembled to perform the necessary calculations. The IAEA [IAEA, 2006] and the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) [NEA, 2004] aid the process by providing a common set of definitions, such as descriptions of the *Scenario* and *Reference Biosphere* concepts.

PAMINA participants share a number of common concepts, although terminology is not always consistent. For example, for one contributing organisation, the receptor is the individual receiving the dose, whereas other organisations use the term receptor to mean the abiotic component of the biosphere into which groundwater discharge. The key terms and concepts that are generally used are outlined below.

10.3.1 Biosphere Concept

As noted in Section 10.1, the IAEA [IAEA, 2007] defines the biosphere as *"that part of the environment normally inhabited by living organisms"*. The IAEA [IAEA, 2007] notes that:

"In practice, the biosphere is not usually defined with great precision, but is generally taken to include the atmosphere and the Earth's surface, including the soil and surface water bodies, seas and oceans and their sediments. There is no generally accepted definition of the depth below the surface at which soil or sediment ceases to be part of the biosphere, but this might typically be taken to be a depth affected by basic human actions, in particular farming."

This is the common, but not unique, understanding of the biosphere in countries participating in PAMINA. In general, the biosphere can be thought of as the receptor for radionuclides released from the disposal facility and geosphere.

In Finland, Posiva's concept of the biosphere makes direct reference to the diversity and variability of the system. In Germany, GRS-B notes that the biosphere is part of the entire disposal system and is treated as such in the safety case. Many contributing organisations note that the biosphere serves no safety function, but that its properties influence the distribution of contaminated groundwater. Similarly, in the UK, the NDA does not consider the biosphere to be a barrier, but instead treats it as a receptor for discharge contaminants. In the Netherlands, the NRG considers the biosphere as a barrier, but does not consider it as part of the engineered barriers, the host rock or the overburden.

10.3.2 Biosphere Description

In Finland, Posiva's description of the biosphere encompasses the climate (including predictable changes in the environment), human habits (for which the nutritional needs and metabolism are assumed to be similar to those of the present-day population), and the routes by which environmental concentrations of radionuclides can lead to exposure. These include use of contaminated water as household water and for irrigation of plants and for watering animals, and use of contaminated watercourses. For Posiva, the evolution of the biosphere includes an additional process not seen in more southerly countries in Europe. The mass of ice during the previous glaciation depressed the crust, such that current land uplift rates (mm per year) will have an impact on the coastline – much of what is currently coastal will transform into terrestrial ecosystems over the next few thousand years. It is perhaps because of this that Posiva considers "reference biospheres" difficult to justify, and directly address evolution of the biosphere.

In France, Andra's general approach for biosphere modelling is derived from Biomass programme [Biomass, 2003]. It takes into account aquifers used for water resources (via wells and deep boreholes), as well as surface water bodies. Soils can be irrigated or may flood, with contamination of crops used for animal and human foodstuffs. The atmosphere is specifically included. Climate change is also taken into account through the use of individual biosphere scenarios, each defined for a specific set of climate conditions. Consideration of the type of disposal (existing near-surface or geological disposal) and life phase of the disposal is a major issue for the description of the reference biosphere to be studied. According to these elements, one temperate and/or several additional future possible biospheres (based on the climate evolution as proposed in Bioclim [Bioclim, 2003]) are taken into consideration. Andra also considered the influence of climate changes on the surface environment over 1 million year through a bio-geoprospective study that included several glaciations cycles.

In Spain, Enresa uses the present-day biosphere as the basis for the description of the biosphere, together with another present-day analogue biosphere in a climatic scenario. The chosen analogue is used to investigate the implications of drier, cooler climate conditions, and the exposure pathways are assumed to be the same as those of the present day.

The present-day biosphere, with its wells and springs, and patterns of food consumption, is also used in the Czech Republic by NRI/RAWRA. Inhalation, ingestion and external irradiation exposures are modelled using food, water and soils from the contaminated area.

In Belgium, Germany, the Netherlands and the UK, reviews of how to treat the biosphere in safety assessment are currently underway. In Germany, the current biosphere model is based on the present-day living habits of the people, and research is ongoing into how to address climate change. Six alternative states have been considered by GRS-B (including the present day), and appropriate analogue locations have been identified as the basis for biosphere description. GRS-K proposal under discussion is to describe a range of hypothetical stylised environments due to climate states that have already occurred at the site over the last one million years.

10.3.3 Treatment of non-human biota

The biosphere descriptions provided by the participants note generally the need to address non-human biota. The European Commission (EC) projects FASSET (Framework for ASSessment of Environmental impacT), ERICA (Environmental Risk from Ionising Contaminants: Assessment and Management) and PROTECT (PROTection of the Environment from ionising radiation in a regulatory ContexT) [PROTECT,**] are cited as the basis for this aspect of the biosphere.

10.3.4 Biosphere Dose Conversion Factor (DCF)

Biosphere transfers can be taken into account either through the use of a set of biosphere conversion factors or by coupling geosphere model with a dynamic biosphere model.

Definition of biosphere conversion factors enables to run independently biosphere and geosphere calculations. They are used to convert any geosphere modelling output into a dose value. Essentially, the biosphere description allows the conversion of J (Bq/year), the radionuclides flux from the geosphere to the biosphere (potentially into different ecosystems), into the annual individual dose D (Sv/year):

$$D = B_{DCF} J \qquad (1)$$

The biosphere dose conversion factor (DCF), B_{DCF} (Sv/Bq) represents the full set of biosphere FEPs for each radionuclide in the assessment.

An alternative approach uses a radionuclide concentration in groundwater rather than a release rate. The units of the biosphere dose conversion factor are then (Sv/year)/(Bq/m^3):

$$D = B_{DCF} C_w = B_{DCF} \frac{J}{Q} \qquad (2)$$

The groundwater concentrations are usually derived from a release from the geosphere, J (Bq/year), by applying a diluting water flux derived from local conditions, Q (m^3/year). Equation (1) is therefore the more generic form of the biosphere DCF.

Commonly the DCFs are calculated using a unit release (1 Bq/year) or unit concentration (Bq/m^3 or Bq/l) as input to the biosphere model. Models are run until steady state conditions are reached or for a pre-defined time (often 10,000 years). The DCF for each nuclide is then the highest dose calculated.

In the assessment model, the dose is then calculated using the release or concentration history of the radionuclide, and the time dependence of the dose is determined solely by the radionuclide release from the geosphere. The biosphere model is then effectively decoupled from the geosphere model by use of the biosphere DCF.

The use of DCF relies on the assumption that the different compartments of the biosphere have a quasi-static behaviour. At every calculation time step, an equilibrium is then reached between the source and the biosphere. The contamination state of the compartments can be considered independent from the history of past releases. This assumption can be assumed to be true as long as the variation of the radionuclide flux from the geosphere remains slow compared to the time required by each compartment to reach an equilibrium. In the context of long-term performance assessment of geological disposal, this assumption is much reasonable for river, plant or animal compartments for which dwelling time of radionuclides are usually shorter than a year. However, it can be more controversial for soil because of possibly much longer dwelling time.

In contrast to the biosphere DCF approach, in some assessments the link between geosphere and biosphere is maintained. In these calculations, the release from the geosphere is input directly to the biosphere model and the resulting time-history of dose contains the dynamics of the release from the geosphere and the biosphere.

10.3.5 Exposed Group

This concept denotes the individual receiving the dose. There must be an individual for whom the dose is calculated. Earlier guidance from the ICRP referred to individuals in the “critical group” [ICRP, 1998], but this has proved to be problematic in terms of defining hypothetical critical groups in the far future. More recently, the ICRP has discussed the concept of the “representative individual”, where highly exposed individuals from a local community are identified on the basis of specific habits and patterns of behaviour.

In the UK, the hypothetical critical groups are referred to as “potentially exposed groups” in the GRA [EA, 2009]. In Germany, according to current radiation protection ordinance, 6 age groups are considered. GRS-K has suggested that in the future the most exposed group should comprise around 30 individuals from all ages. After 1,000 years, the dose calculations can be limited to adult males. This size should allow self-sustaining conditions to be met. Most contributing organisations apply the “critical group” concept in a relatively straightforward way by assuming that the most exposed group would consist of subsistence group consuming its own produce, derived from the most contaminated parts of the environment.

In Finland, Posiva is required to calculate doses to inhabitants of a landscape which is assumed to be contaminated. As noted in Section 10.2, the communities and individual lifestyles are specified. The unusual notion of “other people” represented by a larger population than the most exposed groups is introduced and specific low dose constraints must be complied with. Posiva derives the distribution of annual doses to all individuals exposed by the contaminated landscape. From this distribution are doses to representative persons for *the most exposed group* and *other people* identified.

In France, Andra calculates doses to individuals in the age groups infant (3 months to 5 years), children (6-15 years) and adults (16-70 years) by using the recommended dose coefficients for 1 year old infant, for 10 year old child and for adult. Depending on the context of the assessment (type of disposal, timescales under consideration…), Andra considers for the operational phase a reference group having present-day observed habits at local scale and for the post-closure (on the long term) hypothetic reference or critical groups representative of the individuals that could receive the highest dose. The method (in coherence with Biomass) considers a priori about 10 hypothetical groups with specific habits not necessarily observed at local scale but covering different transfer pathways with the view to not excluding future possible behaviours that are not possible to predict today. The objective is to determine the group representative of the maximum potential exposition (see Section 10.4.1).

Other organisations assume only adults, on the basis that the annual dose to an adult is indicative of the dose over a full lifetime.

10.3.6 Assessment End Point and dose constraints

The end point of safety assessment calculations is a numerical value that can be compared to the regulatory requirements discussed in Section 10.2. In all cases, the calculated dose is the cumulative value from multiple parallel exposure pathways. In practice, calculated long-term doses are always safety indicators since they are hypothetical doses received by representative individuals. Indeed, some contributing organisations have regulatory frameworks that make a distinction between situations for which the calculated dose is considered as a limit and situations for which it is rather a reference that requires alternative safety indicators to be assessed as end points. Those situations may be characterized by the timescale into consideration on one hand, and the likelihood of the features, events and processes that are modelled on the other hand.

In Germany, GRS-K suggests calculating dose over the first 1,000 years following closure of the disposal facility, but the same quantity is interpreted as a “safety indicator” for subsequent times. For example, Finnish regulations require the use of alternative safety indicators in the longer term (radioactivity release to the environment) and the dose assessment part of the safety case is only to be used for several thousand of years. Posiva also calculates “complementary safety indicators”, for example in the form of the activity inventory in different compartments of the model. Retained fractions – the total amount of activity remaining in landscape model compartments as a function of time – are also used. The end points of the Posiva dose calculations are Annual Landscape Doses to representative persons for the most exposed, and all exposed, individuals inhabiting the landscape.

In France, the current ASN guidance [ASN, 2008] makes a distinction between exposure resulting from normal reference scenario and that which would result from random events which disturb the disposal system. For the reference scenario, individual dose equivalents must be limited to 0.25 mSv/year for extended exposure associated with natural external events which are certain or highly probable as well as with events linked to the creation of the disposal, construction defects and expected degradation of the components. This limit of 0.25 mSv/y is only considered as a reference after 10 000 y and the radiological assessment must be completed by qualitative appreciation of the possible evolution of the geological medium. The ASN guide also recommends to treat so-called “altered situations” that should cover uncertain events (natural or linked with human activity). To maintain consistency between exposure in the reference situation and potential exposure associated with hypothetical altered situations, consideration may be given to using the risk concept (the product of the probability of the occurrence of the event and the effect of the associated exposure) to allow for the probability of occurrence of each situation giving rise to exposure. But the definition of a criterion based on an individual risk limits precautions, as it may imply a debatable equivalence between reducing the probability and reducing the exposure. Furthermore, it can be expected to be difficult, if not impossible, to estimate the probabilities of the events which can result in exposure. Under these conditions, the acceptability of individual exposure associated with the occurrence of random events is assessed with allowance made for the nature of the situations taken into consideration, the duration and the nature of the transfers of radioactive substances from the canisters to the biosphere, the properties of the pathways by which people can be affected. Therefore, individual exposure expressed as a dose equivalent, associated with hypothetical altered situations that should be considered for conception of disposal must be maintained below levels liable to give rise to deterministic effects [ASN, 2008]. Except for the comparison with the above cited values, appreciation of the radiological impact results from the efforts made by the developer in the disposal concept so that individual exposition will always be As Low As Reasonably Achievable (ALARA), counting for economic and social factors.

10.4 Treatment in the Safety Case

In this Section, we first provide a brief country-by-country summary of the approach to biosphere modelling/assessment in the participating programmes (Section 10.4.1), and then summarise commonalities and differences in approach (Section 10.4.2). The Section concludes with a one-page tabulation of the biosphere assessment codes and databases in use by the participating programmes (Section 10.4.3).

10.4.1 Biosphere Modelling/Assessment Approaches

Belgium: As in other countries, a staged approach to assessment and disposal facility development is being followed in Belgium. ONDRAF/NIRAS is preparing a safety and feasibility case (SFC-1) on geological disposal options for 2013. The most recent assessment of the potential for geological disposal in Boom clay, SAFIR 2, was published in 2001 [ONDRAF, 2001]. Treatment of the biosphere employed a normal evolution scenario (NES) containing FEPs that are certain, or almost certain, to occur. Alternative evolution scenarios (AES) were also considered. The NES used the present-day biosphere as the benchmark, as it is recognised that future conditions and changes of behaviour are difficult to predict. The NES was therefore a constant biosphere; however, alternate climate conditions were evaluated as modifications to the NES base case. The AES cases dealt with potentially disruptive events whose occurrence is uncertain, but which might have high consequences.

The geosphere-biosphere interfaces considered were a well, surface water (river or pond) and soil (where the aquifer extends to the rooting zone of vegetation). Doses were calculated for food and water intake, inhalation of contaminated air, and direct external irradiation from soil, water or sediment. Radionuclide transport in watercourses was modelled, as well as accumulations in agricultural soils. The alternative climate states were represented by a modified water balance (including increased water consumption by members of the exposed group), with respect to the present-day system. The AES dealt with the possibility of an exploitation borehole drilled into an aquifer underlying the host clay. The effects of glaciation were also considered, including the potential for a severe glaciation leading to erosion of the site itself, with subsequent more direct exposure to the waste, were humans to return to the site during the subsequent interglacial period.

The SAFIR 2 study focused on the conduct of deterministic calculations.

Czech Republic: Long-term safety assessment of a geological disposal facility in the Czech Republic is following a staged approach, and a candidate site has yet to be chosen. Initial assessments in 1999 used a simple drinking water pathway in dose calculations [Lietava, 1999], but subsequently, multi-pathway models have been introduced for a generic geological disposal concept [Landa, 2008]. Three potentially exposed groups are identified, based on alternative conceptualisations of the biosphere: a “farmstead”, a “highland area”, and a “fishpond area”. DCFs for each of these have been calculated for a range of radionuclides. The DCFs are quoted as (Sv/year)/(Bq/m^3), so the geosphere-biosphere interface is interpreted in terms of a water concentration in an aquifer/well (farmstead), aquifer interacting with soil (highland area), or a pond (fishpond area).

Finland: The biosphere models employed by Posiva are richer in detail and complexity than in other countries. The modelling procedure is iterative with a safety case plan produced in 2005 [Vieno, 2005] and updated in 2008 [Posiva, 2008]. A comprehensive biosphere assessment will be reported during 2009. The Biosphere Description 2006 [Haapanen, 2007] will be updated and extended with emphasis on providing the necessary data for more detailed modelling. Posiva aims to submit an application for a construction licence in 2012.

The Olkiluoto site is on the south-western Baltic coast of Finland. The site is undergoing isostatic readjustment as the crust rebounds from the load of ice imposed on it during the previous glaciation, and attention is being given to radionuclide releases at far future times potentially occurring to a range of biosphere types and ecosystems. Typically in southern Fennoscandia, the overburden comprises a relatively thin layer of Quaternary material. The thickness is usually no more than a few tens of metres and there are relatively short geosphere transport paths from the disposal facility to the biosphere. Potential release points over the landscape can be traced back to canister failures at different locations in the disposal facility, and it is considered necessary to model radionuclide releases into a range of ecosystem types at different locations in the landscape. Also, land rise means that it is necessary to account for the transition from one type of ecosystem to another as, for example, a lake forms from the Baltic and infills to produce a wetland, which may subsequently be converted to farmland.

In the dose assessment are the relevant releases from the geosphere directly used to calculate the distribution of the Annual Landscape Dose (ALD). The main assumptions and data underlying the ALD are:

- Exposed individuals spend all of their time in the contaminated parts of the landscape,
- Exposed individuals make full use of food/water production capability of the landscape,
- Estimation of the exposure from food ingestion is based on the annual demand for carbon (production and carbon content weighted average over all edible products in the ecosystem), instead of the traditionally used annual ingestion of different foodstuffs,
- The dose contribution from ^{14}C is calculated using a specific activity model.

Because of the application to a real site, Posiva is confident that the biosphere descriptions employed are valid expressions of potential future conditions. Details are included of FEPs characteristic of the land uplift history, lakes/wetlands and their surroundings, rivers and riverbanks, and historical dwelling and living space, self-sustaining communities (smaller villages), and large-scale land use.

The main assessment calculations are deterministic, but probabilistic techniques are used in supporting sensitivity analyses.

France: The French geological disposal programme is focused in a single area of France, and is currently at a stage of detailed site selection within that area. In 2005, Andra submitted the “Dossier 2005 Argile” which demonstrated the feasibility of a geological disposal in the Callovo-Oxfordian clay investigated with the Bure underground research laboratory operated in Meuse/Haute-Marne [Andra 2005a and 2005b]. Regarding the treatment of the biosphere, the Bioclim method was applied to identify the biosphere-type of the Meuse/Haute-Marne area. This modelling considered:

- The case of a "normal" evolution, by leaving the current state of the concentration level of CO_2 in the atmosphere,
- The possibility of an altered evolution, modified by the continuation of the human actions, by taking into account future CO_2 discharges (main greenhouse gas), according to strong hypotheses on the future discharges of CO_2 (increased) and on the dynamics of the atmospheric carbon cycle.

Generally speaking the results of climatic models, whatever they are, remained imprecise, in particular because of uncertainties concerning the climatic parameters (values of temperature and pluviometry), but they gave a strong answer onto the dynamics of the evolution (distribution in time of the periods of warmer and colder climates).

From the climatic modelling applied to the Meuse/Haute-Marne area, three biosphere types could be deduced:

- The Temperate Biosphere type which may be present at any temporal scale and any scenario of the global climate evolution,
- The Cold Biosphere type, which may be possible for any climate evolution scenario after some 50,000 years, particularly if no anthropogenic effects are superimposed.
- The Warm Biosphere type which is potentially possible up to the 600,000 years period as a consequence of global warming climate perturbations

In coherence with the Biomass method, different (hypothetic) reference groups have been considered by Andra including complete self-sufficiency. These groups were defined by their age, their lifestyle and their eating habits. In line with the ICRP81 and RFSIII.2.f recommendations, the group's nutritional habits and lifestyle were determined on the basis of current knowledge relating to similar contexts. These were defined on the basis of lifestyles as they are known today, without attempting to anticipate their evolution, as this cannot currently be reliably predicted.

The individual in the hypothetic reference groups represented in the calculation used similar farming techniques to ourselves, but relied mainly on his own production to subsist. Although unrealistic in the context of the Meuse/Haute-Marne site, the influence of total self-sufficiency was also tested, as this assumption covers the uncertainties relating to future changes.

The following specific groups have been considered for sensitivity studies with respect to the selected group: beef and dairy farmers, sheep farmers, pig farmers, fowl breeders, grain producers and hunter/gatherers.

The main difference between these groups was that they mainly consume the food product they specialise in producing, consuming very large quantities of it, and that they are self-sufficient for the product in question. Such groups are, by definition, hypothetic and unrealistic.

The (hypothetic) critical group was made up of adults. Andra also tested the possibility that children or infants would be exposed as sensitivity analysis.

The reference hypothetical group was living in temperate climate, equivalent to that prevailing these days. This reference hypothetical group for the assessment is represented by an agriculturist living for the most part on his own products (from their own harvest and drinking water from their own wells: drinking water, irrigating a vegetable garden, watering and raising livestock from their own cereal harvest), whose dietary behaviour is characteristic of the Meuse/Haute-Marne region and based on the surveys of the National Institute of Statistics and Economic Studies (INSEE). This group has been used in the model since it combines the largest number of relevant opportunities for exposure and is highly representative. Food consumption arises from INSEE's surveys.

The basic safety rule RFSIII.2.f, specified that *“the outlets shall consist of rivers and shallow water wells“*. The development of water circulation models (actual and at 1,000,000 years, considering geomorphologic evolution associated to climatic cycles) at sector scale allowed for the identification of the various possible outlets, i.e., locations susceptible of producing water containing radionuclides released from the repository. The selection of outlet locations within each hydrogeological model (actual and 1,000,000 years) is based on a pessimistic approach (selecting a zone with maximum radionuclide concentration levels). The water resource that fed the reference hypothetical group came from a well, but the possibility of using river water (Saulx for example) was tested including potential fishing.

Climatic changes that will happen will be marked by alternate temperate and cold or even glacial periods on the very long term.

If a ”cold” climate prevailed in the site, though, the group of agriculturists defined in the context of a temperate climate would remain the most pessimistic critical group, although they would be less likely to be found in such a context. However, Andra has studied groups living in transient manner (semi-nomadic pastoralists) more realistic in a glacial climate. Warm conditions may occur at early stage mostly from CO_2 effect. This type of biosphere was not studied in the framework of the “Dossier 2005 Argile” [Andra, 2005].

Once this framework has been established, the uncertainties regarding the biosphere related to:

- The choice of the critical group, from among the possible choices, taking into consideration its standardised character and the characteristics of the site, climatic ones, in particular, quantification of the transfer paths of elements into the biosphere.
- The parameters connected to the biosphere call for two types of data. Certain of these are related to the site (climate, soils, living practices) but are independent of the radionuclide or toxic chemical being considered.

Others are dependent on the particular chemical in question: these characterise physical, chemical and biological phenomena which allow the transfer of elements. Sensitivity studies have been conducted to characterise the variation in impact as a function of transfer factor values between the different elements of the biosphere: taking account of the possible variations (habits of the (hypothetic) reference group, transfer parameters) and including an uncertainty dealing with water consumption.

As another example, the uncertainty in the biosphere conversion factor for ^{36}Cl includes the uncertainties connected to the specific parameters of the model (for example, the concentration in stable chlorine in the neighbouring environment), of the site, and of consumption.

Andra considers that the Dossier 2005 marked progress, in that, for the first time in the development of the safety case in France, it explicitly envisaged the influence of climate changes on the hydrogeological model and on the biosphere.

The comparison to international practice showed, moreover, that the values used by Andra are in accordance with standard practice.

During the review of the Dossier 2005 by regulators, the biosphere issue was the object of discussions in particular for the critical group and its food needs. Considering the plurality of models to calculate the transfer in the various compartments of the biosphere, the possible climates on the site of Meuse/Haute-Marne on the long term, potential activities of one or several critical groups and their associated eating habits, the approach for their consideration is being clarified.

As a consequence, the method is currently being developed and consolidated and will aim at to be applicable to all potential repository (existing Centre and future projects) and for all their life phases (operational to long term after closure).

Germany: Safety assessment work focuses on disposal in salt formations. GRS-B has used a stylised biosphere with certain parameter values fixed by legislation, based on the present-day biosphere in the vicinity of the disposal site. The model has been used, e.g. in licensing the Morsleben site for the disposal of low-level and intermediate-level radioactive waste [Storck, 2004], and in a generic study of the disposal of heat-generating waste [Buhman, 1991]. GRS-B uses a generic biosphere assessment model for all radionuclides. DCFs calculated using the model are quoted in terms of (Sv/year)/(Bq/m^3). The geosphere-biosphere interface corresponds to a well, and farming pathways are modelled, allowing for irrigation of soil and crops. Humans and animals consume the crops and drink well water. External and inhalation exposures are also calculated [Pröhl, 2002].

Within research projects alternative climate states (contingent on altered groundwater resource exploitation and modified water balance) have also been considered. So far, each climate state has been evaluated independently in a climate sequence, but ongoing development is considering the possibility of modelling transitions between climate states. Of concern is whether explicit consideration of climate transitions in a model simulation might lead to higher doses than under the assumption of a steady-state biosphere.

Doses have been calculated deterministically, although probabilistic methods are under consideration.

Netherlands: The most recent safety assessment in the Netherlands is PROSA (PRObabilistic Safety Assessment) [Prij, 1993], a generic assessment of geological disposal in salt. The PROSA biosphere model assumed that radionuclide releases would be to river water with potential contamination of the marine environment. Three critical groups were considered: an arable farmer, a cattle farmer, and a sea fisherman. The members of these populations were mainly distinguished by their food consumption patterns. Doses to the arable farmer and the cattle farmer were found to be identical. The dynamic nature of biosphere concentrations was noted, but the DCFs used in calculating dose were based on the distribution of radionuclides in the environment after 10,000 years.

Spain: Enresa’s assessment modelling has so far focused on generic sites in the Spanish climate context. A critical group is defined as a small community that raises all their aliments using water that contains radionuclides from the repository. Of the different potential sources of water, the source that produces the highest doses is selected. Uses of the water are consistent with the production capability of the water source.

Doses are calculated for an adult, who is an average member of the critical group, that is assumed to consume average amounts of various foodstuffs (as per present-day patterns), based on work undertaken in the IAEA Biomass project [Biomass, 2003].

Dilution at the geosphere-biosphere interface determines the concentration of radionuclides entering the biosphere (in a well or a river). From these water concentrations, the distribution of radionuclides in soils, crops, livestock and drinking water is calculated. Consumption of contaminated food and water, inhalation of airborne contaminants, and external doses are calculated for each radionuclide - to give the DCF in terms of (Sv/year)/(Bq/m^3). A river and two types of well are considered (shallow and deep).

Steady-state concentrations in soils are used to calculate doses. These concentrations assume a constant irrigation rate. A continuation of present-day biosphere conditions is assumed in the reference case calculations. Dose calculations are also undertaken for alternative climate states, based on data derived from locations elsewhere having similar conditions to those expected in the future in Spain.

Both deterministic and probabilistic calculations are performed, enabling the calculation of distributions of DCFs. However, only the best-estimate values are used in the calculation of dose, and the probabilistic results are used to analyse the uncertainty in the biosphere model.

United Kingdom: The UK government is currently seeking potential volunteer communities in locations with suitable geological environments for the disposal of higher activity wastes. A range of potential biosphere types, corresponding to typical UK biospheres, is under review by the NDA. However, there is two decades of assessment experience in the UK, with the most recent assessments being those in [Nirex, 1997 and 2003]. Further development of biosphere models is based on the Biomass reference biospheres methodology [Biomass, 2003], and is part of a graded approach that will incorporate site-specific detail when candidate sites become known.

In the NDA concept, the biosphere comprises the near-surface environment of surface fresh waters, surface water catchments, estuaries, the marine environment, and the atmosphere. Stylised biospheres with a credible narrative for landscape development are to be employed [Thorne, 2006], and the possibility of modelling landscape evolution is under consideration [Bioclim, 2004]. Members of the Potentially Exposed Groups (PEGs) are assumed to be exposed to radiation via the following routes:

- Ingestion of crops grown in soil infiltrated by contaminated groundwater and irrigated with water from a well,
- Ingestion of milk and meat from animals grazing in the discharge area and watered with well water,
- Ingestion of soil (as a contaminant of foodstuffs such as open-leafed vegetables),

- Drinking water (from the well),
- Ingestion of freshwater fish (from streams and rivers in the discharge area),
- Inhalation of dust (e.g., soil),
- External exposure from contaminated land.

The NDA is undertaking further work in the following areas: climatology, landform evolution, ice-sheet development, near-surface hydrology and radionuclide transport, soil-plant radionuclide transfer and uptake into the food chain, description of PEGs, and radionuclide-specific research (e.g., on ^{14}C, ^{36}Cl, ^{79}Se and ^{129}I). The NDA is also keeping abreast of the work to establish radiological protection standards for non-human biota in the EC-sponsored Fasset, Erica and Protect projects [PROTECT, 2008].

10.4.2 Identification of commonalities and discrepancies

On the basis of the elements presented in Sections 10.2, 10.3 and 10.4.1, this section contains a compilation of the main common trends in treating the biosphere between participating organisations as well as the major discrepancies that can be highlighted.

Phased approach to assessment: One of the major features distinguishing one contributing organisation from another is the stage reached in the disposal programme. The most advanced programme is in Finland, with detailed site characterisation work underway for some years at Olkiluoto and a licence application to construct the disposal facility scheduled for 2012. The detail and complexity of the biosphere models in the Posiva safety case are at a higher level than elsewhere. Nevertheless, many of the contributors note their use of a phased or graded approach to biosphere assessment to take account of the different stages of the disposal programme (and the national programmes of contributing organisations range from generic studies, to site selection, to licence application at a particular site as presented in Chapter 3). Following this staged approach, other organisations are progressing towards more detailed models, as more information becomes available.

The exposure mechanisms considered: Multiple exposure pathways are generally studied but those selected depend on the exact nature of the hydrogeological and climatic environment on the disposal as well as on human habits. The exposure mechanisms considered are common to all contributors. Consumption of contaminated foodstuffs and water contribute to the annual ingestion rate in terms of Bq/year. Similarly, inhalation doses are calculated on the basis of airborne dust concentrations. Conversion to dose via these pathways is facilitated by a set of Dose Coefficients (DC) documented by the ICRP [ICRP, 1990], which gives the dose per unit ingestion or inhalation as Sv/Bq. Theses DCs have been used by all contributing organisations that have carried out assessments over the past decade. Of the participants, the only group to employ an integrated approach, where the biosphere models are coupled directly to the geosphere, is NRG in the Netherlands. External irradiation exposure is also common to all participants' biosphere modelling programmes, although there is not a common set of conversion factors that give the external γ-dose for uniform soil concentration. Some organisations also calculate the external dose from immersion in water. This may include both a β-dose and a γ-dose.

Assumption of present-day conditions and consideration of climate-change scenarios: It is commonly agreed that the present-day biosphere conditions at the site represent a useful benchmark for assessment of future radiological impacts. Assuming a continuation of the present-day system allows potentially exposed groups to be identified. Modifications to the description of the present-day conditions also allow climatic change to be addressed.

For major system evolution, alternate non-sequential steady states of the biosphere system are commonly used as a basis for assessment, following the Biomass approach [Biomass, 2003]. The participating organizations have a variety of means of specifying stylised scenarios accounting for climate evolution through the study of the past and current environments to develop representative biosphere states from analogue sites in the world (NDA, GRS-K, Andra, Posiva, Enresa…) and consideration of the future impact of greenhouse effects and other human activities (Enresa, Andra, Posiva). For Posiva, system change, driven by land uplift, is so rapid that it is an essential part of the normal evolution scenario that must be addressed in the assessment model.

Dose constraints and timescale/situation dependency: Radiological dose is mainly used to express the hazard posed by the disposal of radioactive waste. However, as seen in Section 10.2, there is a range of dose constraints specified in different national programmes. While Euratom Directive 96/29 [Euratom, 1996] provides a value of 1 mSv per year as the upper limit of chronic exposure for members of the public, the way in which this is interpreted for radioactive waste disposal facilities varies among the participating countries. Regulators in several countries have set a limit for disposal facilities of 0.1 mSv/year, while others have set limits of 0.25 or 0.3 mSv/year. For lower probability (alternative) exposure scenarios, a higher dose limit of 1 mSv/year is used in some countries while others don't specify any limit in that case. In Spain and the UK, the key performance measure is an individual risk of 10^{-6} yr^{-1} for all scenarios (corresponding to a dose of 0.02 mSv/year assuming a probability of one of the exposure occurring).

A key difficulty in dealing with the longer term concerns the large uncertainty associated with evolution of the biosphere. A 10,000-year or longer quantitative dose evaluation is envisaged by most participants. There is an agreement that dose calculations far into the future should not be interpreted as true expressions of radiological hazard, but as an illustrative measure of system performance that could be complemented with other safety indicators.

For some organisations (GRS-B, Posiva), additional safety indicators for the longer times are under discussion or already required by the regulator. In other countries, the calculated doses are seen as sufficiently representative safety indicators even over the longer term.

Perturbations to the expected evolution of the system cannot be ruled out, and their possible health effects must be addressed. The normal evolution scenario is thus supported by altered evolution cases which, taken together, support the overall safety case without necessarily expressing health effects for far future conditions other than in an illustrative fashion. Annual individual dose may still be used as a performance measure, but the numerical value may be assessed by taking account of the likelihood of the initiating event occurring. Case-by-case evaluation of such scenarios is appropriate, noting that there is the possibility that some events could lead to relatively high exposures, but for which the likelihood of scenario initiation is extremely low (high-consequence/low-probability scenarios).

Regulatory guidance/fixed parameters, exposed groups: There is a wide range in the level of prescription and advice provided in regulation with regard to biosphere modelling and the consideration of exposed groups. For example, current German regulations specify parameters for use in biosphere modelling and require that organ doses be evaluated, as well as whole body effective dose equivalents. Finnish regulators also prescribe some aspects of the biosphere model. Posiva's Annual Landscape Doses is an expression of the potential radiological impact on exposed members of the local population. This is set by regulation to be no higher than 0.1 mSv/year. The regulators also specify that the developer should assume that "other" members of the public live at a regional lake or at a coastal site. These other members of the public should be exposed to any repository-derived radionuclides in these watercourses at no more than "insignificant" levels, specified as a dose of no more than 0.01 to 0.001 mSv/year, depending on the number of individuals affected – for larger groups the lower limit should be considered.

In other countries, there is a range of interpretations of what constitutes the "critical" or "most exposed" group for whom the exposures are evaluated. Most contributors to this study calculate doses for a traditional critical group defined by present-day habits and practices. Where more than one group is evaluated, the groups are described in terms of location and lifestyle, for example sea fishermen and farmers (arable and cattle) in the NRG case, and farmers, highlanders and fish farmers in the NRI case. The NDA [Egan, 2008] and Andra have, perhaps, the most sophisticated approach to defining exposed groups. For example, Andra has adopted the Biomass methodology and considers a range of lifestyles [Andra, 2005a]. For the long term, Andra selects a priori the potentially (hypothetic) exposed reference groups by exploring the transfer pathways within a certain level of autarky (in the site and region for a certain biosphere type), in agreement with the recommendations of ICRP 101 [ICRP, 2006]. This approach consists in exploring the different transfer pathway of the site and region and not exclude a priori some transfer pathway.

Food consumption rates: Radionuclide concentrations in food play a major role in determining overall exposure, and there is some difference as to which consumption rates to apply. Some contributing organisations use average food consumption rates, but assume that all food consumed comes from the most contaminated parts of the environment – the societal context being a self-sustaining farming group. Correspondingly, exposures contingent on location assume maximum times of occupancy of the contaminated areas. Usually there is not assumed to be any dilution of contaminated food from outside the modelled system. Upper limits to foodstuff consumption correspond to the 95th percentile (as adopted by ICRP 101 [ICRP, 2006]) and advocated in Biomass. Andra's approach is based on considering combinations of some foodstuffs at normal consumption rates, and selective high exposure from specific food product (high consumption rates of the product in question). Consumption rates are based on statistics available for the present day, or three times the mean consumption rate if data are not available [Kłos, 2005]. But, in any case, reasonableness, sustainability and homogeneity are baseline for diet definition and extreme behaviours are not considered.

Future climate states based on analogue conditions take their exposed groups and food consumption rates from analogue sites.

Posiva bases its intake model on the total productivity of carbon from the ecosystems represented in the landscape model. This ensures that all available contaminants in the foodstuffs present in the ecosystem reach the exposed individuals (including through primary production of fauna that have consumed local vegetation).

Age groups considered: For most contributing organisations, adults are the age group considered in the assessment, and it is implicit that the adult dose can be used as a measure of lifetime exposure (since environmental concentrations are calculated to vary only slowly). However, Andra evaluates doses to different age groups. Current regulation in Germany also imposes 6 age groups but GRS-K has also proposed to restrict different age groups modelling to the first 1,000 years; thereafter, dose to adult males would be considered to be the appropriate safety indicator.

Assessment philosophy: In Biomass [Biomass, 2003], part of the assessment context was identified as “Assessment Philosophy”. Addressing this aspect of the assessment context requires a statement about whether the aim of the dose calculation is, for example, to be pessimistic, cautious, or equitable. There is a range of assessment philosophies indicated by the contributing organisations. For example, the Posiva assessment aims to ensure that the safety case does not under-estimate or over-estimate the performance of the disposal system. Similarly, GRS-K suggests the use of best-estimate parameter values in assessment. French guide suggests the use of parameter values that ensure that doses are not likely to be under-estimated, a cautious assessment philosophy.

Deterministic vs. probabilistic modelling: The approach to biosphere modelling of most contributing organisations to date has been deterministic, but probabilistic modelling is carried out in some countries (e.g. the Netherlands, Spain), if not as part of the mainline assessment calculations, as an aid in sensitivity analyses.

Many organisations indicated in addition that new underway scientific developments comprise:

Use of radionuclide-specific biosphere models: Current modelling techniques often assume that water balance considerations are a key driver of contaminant transport in the biosphere, and in many countries a single generic modelling framework is used for all radionuclides of interest. However, in some countries, depending on the radionuclide inventory under consideration, some radionuclides, primarily ^{14}C and ^{36}Cl, are treated with radionuclide-specific models. The NDA notes that ^{79}Se and ^{129}I could also be candidates for radionuclide-specific modelling. Posiva, GRS and Andra have alternative biosphere models for ^{14}C, and Andra also models ^{36}Cl and ^{3}H with separate models.

Direct modelling of the **transition between climate states** and associated impacts on the biosphere (e.g., as proposed by GRS-B). Such modelling could consider the influence of transitory climate conditions on the geosphere-biosphere interface. It is of interest if there are radionuclide accumulation and release processes that might lead to increased dose rates during transitions stages.

Non-human biota: There is common ground in recognising that non-human biota should be protected, but it is further acknowledged that, at present, there is not sufficient information to do this to the same level of detail as for models of human exposure. Participation by some of the contributing organisations in Fasset and Erica [PROTECT, 2008] illustrates the importance of international cooperation in biosphere modelling. There is a long history of international studies concerned with biosphere modelling, and many contributors to this exercise participated in the Biomovs (BIOspheric Model Validation Study) [Biomovs, 1993] , Biomovs II [BiomovsII, 1997] and Biomass (BIOsphere Modelling and ASSessment methods) [Biomass, 2003] studies, and are currently active in Bioprota [Bioprota].

Health effects: In general, only radiological health effects have so far mainly been considered in safety assessment calculations. However, some organisations are starting to consider potential health effects associated with chemical toxicity. For example, Enresa considers that chemotoxic elements can be treated using assessment tools similar to the radiological dose assessment. Another example is the evaluation of the impact of four chemical toxics: boron, nickel, antimony, and selenium by Andra in its Dossier 2005 [Andra, 2005a].

In addition, it is worth noting that, in France, Andra is currently developing an approach that aims at harmonizing the radiological assessment methodology for existing near-surface disposals and possible future geological disposal.

10.4.3 Databases and Tools

Table 3 – Summary of tools and databases used in biosphere and dose assessments by the participants.

NRI - RAWRA (Czech Rep.)	Excel, AMBER, GoldSim v9.6, RESRAD v6.4	Algebraic expressions and data are encoded in Excel. For some applications the other codes are employed and results are used for Quality Assurance (QA).
Posiva (Finland)	GIS database, UNTAMO toolbox	Details of the landscape elevations and other spatially bounded data. UNTAMO handles the site data using the ArcGIS environment. Interfaced to the biosphere assessment database.
	POTTI database	Research database for site descriptive data.
	BSAdb	Biosphere assessment database - used for assessment data (in conjunction with other external databases).
	PANDORA / EIKOS	Technical implementation of the biosphere models based on Matlab/Simulink. PANDORA is developed in conjunction with SKB, Sweden, EIKOS is used for sensitivity analysis.
Andra (France)	Aquabios / MoM	Integrated modelling environment containing application-specific database and model definition.
GRS-B (Germany)	EMOS, EXCON, EXMAS	EMOS is an integrated package for safety assessment Including the modules EXCON and EXMAS for calculation of the radiation exposure from radionuclide concentrations or fluxes.
NRG (Netherlands)	FEP database	Library of FEPs for the assessment model.
	MiniBIOS	Distributions of the DCFs for radionuclides transported via groundwater.
	EXPOS	Radiation EXPOSure in terms of maximum dose rates for individuals.
	UNSAM	Code developed to conduct sensitivity and uncertainty analyses of mathematical models.
Enresa (Spain)	FEP database	Library of FEPs for the assessment model.
	AMBER	Modelling tool in which the assessment model is implemented. Used for both deterministic and probabilistic calculations.

A range of databases and tools are employed for biosphere and dose assessments. These are summarised in Table 3.

10.5 Conclusions

This chapter discusses the biosphere programmes in eight European countries participating in the PAMINA Project. These programmes are at different stages of development, ranging from generic studies as a preliminary phase to site selection, to highly sophisticated site-specific landscape models of the evolving surface environment at particular sites. For instance, in contrast to the situation in other participating countries, the Finnish and French geological disposal programmes are active at a single site or area (respectively Olkiluoto and Bure) currently undergoing detailed characterisation. Clearly, the stage of development of the waste disposal programme has a major influence, on one hand on the national regulatory framework in each country, and on the other hand, on the structure of the biosphere model in the safety case and the associated assessment databases.

Depending on the programme stage, the maturity of biosphere modelling approaches and dose assessment strategy differs strongly between organisations. This heterogeneity implies apparent discrepancies in the different strategies for biosphere modelling. But, considering that these strategies may evolve with programme development, common general approaches and tendencies may be observed. They mainly concern:

- A dose limit, or constraint, specified in most countries to ensure that radiological protection criteria are met. The dose limit acts as a surrogate for the health risk posed by potential radiological exposures. For the “normal” or “expected” evolution scenario, dose limits for members of the public are typically 0.1-0.3 mSv/year (based on a fraction of the value specified in [Euratom, 1996]). In the UK the primary regulatory performance measure is expressed as an annual individual risk that can lead to a lower dose. Alternatives are found for protection of the representatives of the most highly exposed individuals for less likely, “alternative” evolution scenarios,
- The interpretation of long-term dose calculations as illustrative performance measures is preferred by moving from the notion of dose limit to a reference or other indicators. At long timeframes (from one or several thousand years up to one million years), it is understood that, where a numerical dose is calculated, the value is more suitable for qualitative evaluation of results and sensitivity analyses,
- The consideration for climate evolution in addition to the definition of a today reference biosphere by, either a set of additional possible biospheres in the future or sensitivity analysis,
- The definition of multiple exposure pathways,
- The definition of food consumption and diet consistent with today habits and database; a reasonable behaviour adapted with the characteristics of the exposed group is preferred and extreme consumption are excluded,
- The identification of specific radionuclides to be modelled with specific models concern ^{36}Cl, ^{14}C, ^{3}H, ^{129}I and ^{79}Se,
- The identification of a need for further consideration of potential impacts on non-human biota, and a focus on assessment of radiological health effects (as opposed to chemical toxicity impacts),

In addition, because of the complexity of the biosphere and uncertainties concerning its treatment in the safety case, most organisations consider that an iterative approach and a good working relationship between regulators and the developer are essential to facilitate development of the safety case in a manner acceptable to regulators.

But, besides those general common trends, it appears nevertheless that the approach between participating organisations differs greatly in a couple of areas: the potentially exposed groups and the age groups considered. There are good reasons for differences – these largely relate to the national regulatory framework in each country. But, contrary to the above observed variations, it seems that those differences are linked to a less extent to the stage of development of the disposal programme but more to the safety “philosophy” developed in the country. Regulatory differences include variation in the level of prescription in regulatory guidance, particularly with regard to the definition of potentially exposed groups and the use of prescribed parameters in biosphere models fixed by legislation. This important issue should probably be more in depth discussed by participating organisations with the view to better understanding the origins of those discrepancies and the needs for harmonisation.

This review also suggests that there could be benefit in an improved glossary of terms in the context of the biosphere.

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11. Modelling strategy

11.1 Introduction

Due to the large time and space scales involved, the long term safety of a deep geological repository can not be demonstrated only through experiments. The safety case requires the development of models that represents different parts or aspects of the disposal system on the basis of a good understanding of the basic processes that govern the system evolution. These models are used to study the future state of the system and the fate of the radionuclides disposed of.

The results obtained with these models, plus natural analogues and any other arguments available will be used to justify that a repository is safe, when presenting the Safety Case. As a consequence, modelling plays a fundamental role in the justification of the long term safety of a repository.

This chapter presents the strategy followed by the different organisations for developing the models used in the Safety Case of geological repositories and the requirements of the regulators on such modelling.

This section is focussed on the modelling strategy followed to produce the Safety Case, not on the models themselves. Some contributions provide detailed descriptions of the models used, in addition to the broad strategy followed for modelling. These models are not presented in this chapter, but can be found in the Appendices.

11.2 Regulations and Guidelines

In IAEA Safety Standards for geological disposal [IAEA, 2006] there are only a few phrases related to models or modelling: "… it is important to recognise that there are multiple components of uncertainty inherent in modelling complex environmental systems and that there are inevitably significant uncertainties associated with projecting the performance of a geological disposal system.", "Quantitative analyses are undertaken, at least over the time period for which regulatory compliance is required, but the results from detailed models of safety assessment are likely to be more uncertain for time periods in the far future", "Justification and traceability both require a well documented record of …the models and data used in arriving at a particular set of results for the safety assessments" and "The representation of future human behaviour in assessment models is necessarily stylised, as it is not possible to predict behaviour in the future with any certainty".

In some countries such as Spain and The Netherlands no detailed regulations have been developed for deep geological repositories, and no specific requirements or guidelines are available on the topic of modelling.

Other countries, with geological disposal programmes at more advanced stages, already have regulations (at least in draft form) or discussions between the implementers and the regulators that provide information on the expectations of the regulators regarding the modelling strategy to be followed to create a Safety Case. In the next sections the information gathered regarding regulations and guidelines from the regulators is presented on a country basis.

Belgium (Bel V and SCK/CEN-ONDRAF/NIRAS): Regulatory requirements and guidelines concerning long-term safety of high-level radioactive waste disposal are still in preparation in Belgium. Preliminary contacts between the operator and the radiological protection authority FANC/AFCN and its technical support organisation Bel V indicate that verification and qualification (see section 11.3) of the computer codes used for the safety assessment can be expected to be essential elements of the Safety Case.

Bel V has identified the modelling strategy as one of the key issues to be considered in the safety assessment of radioactive waste disposal facilities. The results of the safety assessment (and related models) jointly with the confidence building in the results of these models contribute to the safety case and can aid in regulatory decision-making. The opinion of Bel V experts is that the Regulatory Body should assess the modelling strategy of the operator. In this framework validation and qualification of safety assessment models should be the subject of formal approval of the Regulatory Body.

Czech Republic (NRI, RAWRA): According to directions of the State office for nuclear safety (SONS/SÚJB), mathematical models, including screening ones, are necessarily assessed on the basis of international standards, e.g. ISO/IEC 9126 for evaluation of software products and ISOI/IEC 12119 "Information technology – Software Packages Quality Requirement and Testing". Each computer code used for the evaluation of safety of nuclear facilities (and a repository is a nuclear facility according to Atomic Law) must be approved by SONS/SÚJB. The following documents must be submitted for software approval:

- Description of the product including requirements for hardware
- User manual
- Input data
- Testing conditions, which determine how the product should be tested for fulfilling quality requirements
- Requirements for quality of organization and workers implementing the code

Finland (Posiva): The Finnish Regulatory Body (STUK) states about modelling and input data that "In accordance with Section 29 of the Government Decision, the computational methods shall be selected on the basis that the results of the safety analysis, with high degree of certainty, overestimate the radiation exposure or radioactive release likely to occur" [STUK, 2001]. To achieve this it follows that "In order to assess the release and transport of disposed radioactive substances, conceptual models shall first be drawn up to describe the physical phenomena and processes affecting the performance of each barrier. Besides the modelling of release and transport processes, models are needed to describe the circumstances affecting the performance of barriers. From the conceptual models, the respective calculation models are derived, normally with simplifications. Simplification of the models as well as the determination of input data for them shall be based on the principle that the performance of any barrier will not be overestimated but neither overly underestimated.

The modelling and determination of input data shall be based on the best available experimental knowledge and expert judgement obtained through laboratory experiments, geological investigation and evidence from natural analogues. The models and input data shall be appropriate to the scenario, assessment period and disposal system of interest. The various models and input data shall be mutually consistent, apart from cases where just the simplifications in modelling or the aim of avoiding the overestimation of the performance of barriers implies apparent inconsistency."

France (Andra and IRSN): The RFS.III.2.f of 1991 [JORF, 1991], which was the reference for the Dossier 2005 Argile [Andra, 2005], recommended in "*section 2.2.1. Reference situation…The evaluations will be based on a modelling of the repository evolution, in particular of the barriers, and on a modelling of the groundwaters and transfer of radionuclides"* and in *"section 5.4. Modelling The models are simplified representations of the real phenomena: it must be shown, on one hand that these representations do not leave aside important phenomena, and on the other hand that the simplifications of the phenomena have a character pessimistic enough. Considering the importance of the modelling, particular care must be taken in the validity of the models and the data. For that purpose, it will be necessary in particular to participate in inter-comparisons of models"* (not an official translation).

The revised version of this safety rule issued in 2008 [ASN, 2008] includes some specific recommendations about modelling: …."This modelling has to rely upon sound knowledge of the physico-chemical processes and events which can affect the evolution of the repository system and its environment and thus on investigations, as well as an advanced research program"…." Considering the importance of the modelling, a particular care must be taken in the quality of the data…"…" Considering the iterative character of the demonstration of safety, the level of detail of the modelling will also depend on the progress of the studies and on the level of precision of the data which will have been collected at the time of the modelling"(not official translation).

Germany (GRS-K and GRS-B): In the present regulatory frame of 1983 [BDI, 1993] modelling is not mentioned in any detail. Regulatory expectations have advanced since 1983 and a new safety requirements document has been generated [Baltes, 2007], which is expected to serve as draft for a new regulation. [Baltes, 2007] comprises both, the international developments of the past decade (mainly [IAEA, 2006], [ICRP, 1998] and [NEA, 2004]) and the national trends emerging from expert group discussions.

The draft guidelines [Baltes, 2007] demand adequate modelling as one of the crucial ingredients in the performance assessment to demonstrate long-term safety in the safety case. The period of proof is fixed to be one million years. A safety case is requested at specified milestones during the planning and operational phases of the repository development.

The implementer must determine accurately all features, events and processes of the repository system, provide evidence for the scientific understanding of the relevant (and prospectively relevant) processes, generate adequate models, verify and validate the models including the corresponding computer programs, and evaluate the results taking uncertainties into account.

The models to be used in the assessments shall be developed according to established quality assurance procedures. Verification, validation and confidence building shall be carried out according to the state of the art in science and technology. The applicability of the models has to be substantiated, e.g. by means of natural analogues, experiments, in-situ tests and reviews. The issue of upscaling has to be addressed. Where uncertainties exist at a conceptual level, alternative models have to be discussed and, if necessary, to be used. The robustness of the system against model uncertainties should be demonstrated. (The treatment of uncertainties in models is discussed in chapter 13.)

According to the present regulations, the biosphere evolution does not need to be modelled, which accommodates the perception that a prognosis of the biosphere over one million years is not possible on scientific grounds. No safety functions are allocated to the biosphere. For long time frames, a standardised, static biosphere model is used to help assessing the indicators for isolation and containment, which are considered the primary safety functions.

There is no regulatory advice whether detailed or simplified modelling is the preferred strategy. In any case, the implementer must substantiate the applicability of the models and show that the repository system and its behaviour are well understood.

United Kingdom (NDA): Relevant agencies have published guidance, known as the GRA [EA, 1997], which outlines how an application for land based disposal of solid radioactive waste would be judged. A revised version of the GRA was published in February 2009 [EA, 2009]. This regulatory guidance includes a section on Modelling Studies, which main points are reproduced below.

'Modelling studies are likely to make up an important part of the quantitative environmental safety assessment. They may also contribute to or support complementary arguments based on alternative lines of reasoning. As well as the results of the studies, the developer/operator will need to provide details of the models and methodologies used including any assumptions.

The general aim of modelling studies will be to help in understanding the characteristics and behaviour of the overall disposal system and its component parts. However, in order to contribute usefully to the environmental safety case, each specific set of modelling studies will need to have more specific defined and documented objectives:

- *modelling objectives should take account of the decisions that the results are intended to support;*
- *the selected approach should be driven mainly by the modelling objectives, and not by the availability of models or software or by considering what models or software were used previously (unless there is an overriding need for consistency);*
- *modelling objectives should be defined in terms of what can be accomplished with the available data. Complex models should not be developed if there is not enough data to support them;*

- *the objectives should be reviewed throughout the modelling process.'*

'The developer/operator will need to carry out a systematic programme of work to build confidence in the modelling. This will include interpreting raw data and developing and testing conceptual, mathematical and computational models. The process of building confidence in a model for its intended purpose is iterative and progressive. Because of the long timescales to which the models used to support the environmental safety case may need to be applied, it will rarely be possible to have meaningful direct validation by comparing model outputs with observations.

The measures adopted in a confidence-building programme should include:

- *systematic approaches to model building and consideration of alternative models;*
- *iteration between model building, quantitative assessments and data collection;*
- *good communication between modellers (including those developing and using models), suppliers of data (including those planning research or data collection and those actually making observations) and those using modelling results;*
- *continuing peer review of model development;*
- *rigorous quality assurance of all modelling activities and associated data handling, including controls over changes to models and data and a detailed audit trail.'*

11.2.1 Relevant topics

From the detailed regulations and guidelines presented in the previous paragraphs some relevant topics can be identified:

- Regulations do not contain very detailed instructions on how to model. For instance, in the draft of the new German regulations [Baltes, 2007] there is no regulatory advice whether detailed or simplified modelling is preferred.
- Models are needed to evaluate both the evolution of the geosphere and the engineered barriers and the release and transport of the radionuclides from the waste (Posiva, Andra).
- It is considered necessary to demonstrate that all the important phenomena are included in the models (IRSN, Andra, GRS-K).
- Models should try to be realistic, and simplifications should not lead to a gross underestimation of the performance of a barrier (Posiva).
- Simplifications are necessary when developing models. It must be demonstrated that these simplifications are pessimistic, i.e. that they underestimate the performance of a barrier (Posiva, Andra, IRSN).
- The regulator should assess the modelling strategy of the implementer. In this framework validation and qualification of safety assessment models should be the subject of formal approval of the Regulatory Body (Bel V, NRI).
- It is fundamental to demonstrate the validity of the conceptual models and the computer codes used in the safety assessment (SCK, Bel V, Andra, IRSN, NRI, NDA, GRS-K).

- Model development and the generation of data to be used in the models are closely related topics. The quality of the data used in the models must also be justified (Andra, IRSN, Posiva).
- Models must be developed following established quality assurance procedures (GRS-K) and the process of model and data generation must be properly documented.
- Biosphere evolution and human behaviour can not be predicted reliably and an stylized approach is favoured (GRS-K and IAEA [IAEA, 2006]). Guidance is provided to use present ecosystems and habits (Posiva).

11.3 Terminology

The following definitions taken from IAEA glossary [IAEA, 2007] are applicable to all the organisations that have provided contributions on “modelling strategy”. Some organisations explicitly state that they use the IAEA terminology (NEA, NRI, Enresa, Bel V, SCK) while for others the content of the contribution is consistent with these definitions from [IAEA, 2007]:

Model: an analytical representation or quantification of a real system and the ways in which phenomena occur within that system, used to predict or assess the behaviour of the real system under specified (often hypothetical) conditions.

Conceptual model: a set of qualitative assumptions used to describe a system (or part of it). These assumptions would normally cover, as a minimum, the geometry and dimensionality of the system, initial and boundary conditions, time dependence, and the nature of the relevant physical, chemical and biological processes and phenomena.

Mathematical model: a set of mathematical equations designed to represent a conceptual model.

Computational model: a calculation tool that implements a mathematical model.

Model validation: the process of determining whether a model is an adequate representation of the real system being modelled, by comparing the predictions of the model with observations of the real system.

Model verification: the process of determining whether a computational model correctly implements the intended conceptual model or mathematical model.

As stated by SCK/CEN, strict validation of the models used in safety evaluations of geological disposal systems is not possible, because of the space and time scales involved. As a consequence, a new concept is introduced -**model qualification-** that is defined as the process of ensuring whether a model is consistent with scientific understanding within the assessment basis and adequately represents the phenomena and interactions relevant to the assessment case that it represents.

Regarding the terminology used to identify the models used in the Safety Assessment there are significant differences in the nomenclature used but the underlying concepts are quite similar (see section 11.4.2).

11.4 Methodology

The modelling of geological repositories for radioactive waste has evolved significantly since the 1980´s. The initial safety assessment exercises used simplified models and were focused on the mobilisation and transport of radionuclides. Since then, models for the evolution of the engineered and natural barriers have been included in the safety assessment, and more complex and realistic computer codes are available.

The analysis of the contributions received shows a common view on the modelling strategy to follow to develop and demonstrate the safety of a deep geological repository. In section 11.4.1 the main ideas on the general methodology on modelling are presented. Sections 11.4.2 to 11.4.6 further develop some particular topics related to modelling.

11.4.1 General methodology

Since the radiological consequences of the repository are expected to occur after several thousands of years, and continue far into the future, an assessment of those consequences can only be made on the basis of simulations of the evolution of the disposal system and of the resulting transport of radionuclides through the repository system.

The calculations undertaken with these models, plus natural analogues and any other arguments available will be used to justify that a repository is safe, when presenting the Safety Case. As a consequence, adequate models and data are critical to demonstrate the safety of a repository.

Due to the long timescales of the evaluation (around 1 million years), repository modelling requires a sound understanding of a wide range of physical and chemical processes possibly influencing the evolution of the disposal system and the environmental conditions (NDA IRSN and Andra). Model calculations can be trusted only if there exists a good scientific knowledge of the basic processes expected to take place in the repository. To obtain the necessary level of knowledge on these processes a significant R&D programme is required (IRSN).

Model and input data must be developed on the base on the best available scientific and technical knowledge (Posiva, GRS-K). The whole process of model and data generation must be undertaken following quality assurance procedures, and must be properly documented.

When modelling the disposal system it is useful to divide the global system into different components that can be treated separately, as long as the interfaces between components are properly considered (Enresa and Andra). Three different components are commonly considered:

- the *near field* which includes the waste packages, the engineered barriers and the part of the host rock disturbed by the disposal facility,
- the *far field* which corresponds to the geologic part of the repository, that is not disturbed by the repository, and
- the *biosphere* which is the part of the environment where radionuclides come into contact with man and other living organisms (cf. ecosystems).

Models are formulated for a specific purpose and include only the processes and interactions that are deemed necessary. It is clear that a single model cannot represent all the phenomena taking place in the repository (Posiva and Andra). Integrations and justified simplifications are then necessary up to a global safety model (of the total repository system) allowing for impact calculation (Andra).

The hierarchy of models used by NDA and shown in Figure 16 is used by most organisations (although nomenclature may change), but not by Posiva. At the highest level is a total system model which is used to calculate performance measures such as radiological risk or dose. If a probabilistic approach is being used to treat uncertainty, the total system model may be run many hundreds or thousands of times in a Monte-Carlo simulation. Supporting the total system model, and supplying data to it, are much more detailed models of components of the system, which in turn may be supported by process models of specific aspects of the system at an even greater level of detail. The understanding gained from these process and component models needs to be sufficiently represented in the total system model to enable an accurate calculation of overall system performance.

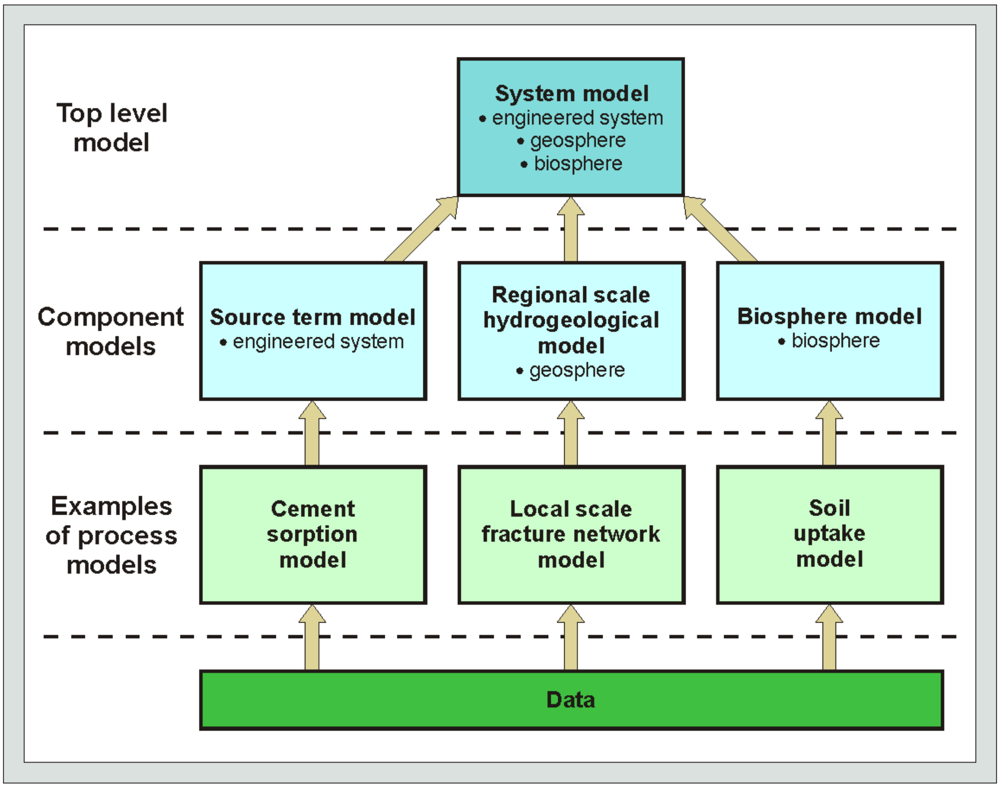

Figure 16 - Hierarchy of models used in the Safety Assessment (NDA).

The development of a safe repository and the demonstration of its safety is a stepwise process that can take several decades from the initial stages to repository closure. The development of models of the repository is a fundamental part of the safety assessment and it will also be undertaken following a stepwise approach. At the early stages of repository development simplified models and generic data are commonly used, but at later stages more realistic models and site specific data are used.

Safety Cases are prepared at selected decision points in the repository development programme (depending on the regulatory requirements). The degree of detail of the models and the quality of the data used must be consistent with the objective of the Safety Case.

The modelling approach is part of the Safety Case and it should be improved for each phase of development of the Safety Case in order to integrate new data and the improvement of knowledge on features, events and processes (IRSN).

The modelling approach and models will evolve with time, but it is important to follow a frozen modelling strategy and use frozen models in each iteration of the Safety Case, to ensure transparency and traceability. In each iteration the possible model improvements and data needs for the next step should be clearly identified and documented (Bel V). In addition, feedback will be provided to the repository design and site characterisation programmes.

11.4.2 Model classification

Contributing organisations classify the models used in the Safety Assessment following different criteria and thus, different nomenclatures are used.

SCK/CEN distinguishes three types of models:

- models used in the framework of phenomenological research to analyse and explain results of experiments, usually known as *process models*;
- models used to simulate the *evolution* of the repository system;
- models used to simulate the *transport of radionuclides* through the whole repository system or through parts of it.
- In this last group of models a distinction is made between *performance models*, which are used to quantify indicators that illustrate the performance of specific system components or safety functions and their contributions to overall system performance, and *safety models*, which are used to evaluate safety indicators such as dose and risk.

For GRS-B models used in the safety assessment are developed and applied on two different levels: *detailed models* to characterise the evolution of sub-systems, or the impact of specific processes, or to generate input data for the integrated models, and *integrated models for consequence analysis* for selected scenarios of the repository system. Detailed models are used to simulate laboratory and in-situ experiments and to better understand specific processes or the performance of subsystems as a whole. In some cases such modelling approaches are directly implemented in integrated models for consequence analyses. However in most cases, when identified as relevant, the respective process is implemented in a simplified form. Some of the detailed models are only used to generate input data for integrated models.

Enresa and IRSN classify the models used in the safety assessment as follows:

- *Process level models* (that can be quite complex) are developed and used by R&D groups in order to reach a scientific understanding of (and identify the basic processes that control) a limited part of the disposal system evolution. These models usually are not included explicitly in the safety assessment, but they constitute part of it and their results are used to build the models used in the safety assessment or generate data for them.
- *Integrated models* that are used by the team that prepares the safety assessment (or by supporting R&D groups) to represent the evolution or behaviour of a part of the disposal system during a given time period. These models are built on the basis of the previous process level models, making simplifications and taking into account the characteristics of the disposal system. Integrated models are used to predict the evolution of the different parts of the disposal system, generate input data for the consequence analysis and perform the consequence analysis. The global *model for consequence analysis* is a particular case of an integrated model that represents the whole disposal system and is focussed in radionuclide mobilisation, transport and radiological consequences.

Posiva identifies 2 categories of models used in the Safety Assessment, those related to *system evolution* and those related to the *migration of the radionuclides*. Some other models similar to the category of process level models are utilised within the repository programme, but they are not directly included in the Safety Assessment. Instead, the scientific understanding and related uncertainty is formally communicated through, and documented in, the Models and Data report.

NDA identifies 3 categories of models: *process models*, *component models* and *total-system model*, as can be seen in Figure 16 .

Although there are important differences in the terminology used, a similar structure can be identified. In terms of their purpose, models can deal with system evolution or radionuclide migration. In terms of their degree of detail and part of the repository represented 3 types of models are used: process level models (very detailed), integrated or component models and the model of the whole repository used for consequence analysis.

In its Dossier 2005 [Andra, 2005] Andra uses two levels of a model classification based first on their destined use and then based on the knowledge acquired for each phenomenon. The first level of classification considers three types of models:

- *Phenomenological models*: developed and discussed in the scientific community for understanding the processes.
- *Conceptual models*: simplified but justified representation of key phenomena or parameters, generally used for preliminary calculations to test the influence of those parameters or phenomena.

- *Safety calculation models* which correspond to the mathematical representation of the repository in order to evaluate radionuclides transfers.

Following this classification, an additional classification was used in relation to the degree of knowledge acquired on phenomenon or data:

- A *best estimate model*, is either, the model that is based on the most comprehensive understanding of the phenomena to be modelled, and whose ability to account for direct or indirect measurements has been confirmed, or in comparison with other available models it might be the one offering the best match between the reality that it is supposed to represent and the numerical results that it generates in the impact calculation.
- A *conservative model*, addresses a case in which it is possible to demonstrate that its use, all things being equal otherwise, tends to overestimate the repository impact, compared with the results that would be obtained by taking into consideration all the relevant phenomena in the chosen parameter variation range.
- A *pessimistic or penalising model* designates a model that is not based on phenomenological understanding, however empirical, but that definitely overestimates the repository impact.
- Finally, an *alternative* model stands for a model that can not be classified according to the above three items. This category covers models that appear to be more comprehensive than the selected reference model but have been less thoroughly validated.

Andra uses the same type of classification for parameter values.

11.4.3 Simplifications

When modelling a complex system such as a deep geological repository, simplifications are unavoidable. Nevertheless, models must be sufficiently detailed to describe the behaviour of the system and its components in order to provide a basis for the assessment of the performances over the time of interest and to ensure the compliance of the system with the safety objectives (IRSN). The hierarchy and classification suggested by Andra in the Dossier 2005 [Andra, 2005] is an illustration of the different stages of simplifications from detailed complex scientific models, to conceptual models and then to calculation safety models.

Different types of model simplifications are introduced for the various modelling applications in a Safety Case (SCK/CEN).

- A first type of modelling simplifications is introduced when process models are converted into models describing the evolution of the repository system or into transport models used for safety and performance modelling. At this level the essential processes that dominate the considered evolution or transport mechanisms, and the processes that can be neglected because they have a negligible or a limited positive influence can be identified.
- A second type of simplification can be applied at the level of the numerical codes. The existence of symmetry planes allows a reduction of the modelled domain; neglecting a

minor transport phenomenon, e.g. advective transport in a clay formation whose contribution is small in comparison to that of diffusive transport, can allow a further reduction of the modelled domain and the use of faster numerical algorithms.

- In the past, a third type of simplifications was often needed to overcome limitations in the available computer codes or in the calculation capacity of the computers. This type of simplifications was common during the nineties. As three dimensional computer codes were not available or required excessive calculation times, the real problem had to be approximated by 2D or 1D models. The availability of more powerful computers and codes in recent years has reduced the need to use such simplifications in deterministic calculations. Stochastic calculations (i.e. Monte Carlo simulations) often need further simplifications in the models to reduce the required calculation time.

NDA believes that there is value in modelling a system at various levels of complexity. Simple analytic expressions or very simple models can be useful for communication purposes and build confidence in the results of the complex numerical models, by showing that similar results are obtained using simple models whose basis may be more easily explained and that can be shown to capture the essential features of the system. This agreement between simple and complex models would demonstrate a good understanding of the repository behaviour and that the key processes and parameters have been identified.

The scientific knowledge and applicable data will increase with the successive steps of the repository development. In particular, when a site becomes available, the site characterisation programme will provide a great amount of information. As a consequence, the realism and complexity of the models used in the Safety Assessment (as well as the data quality) are expected to increase in successive iterations of the Safety Case. As an illustration, the peculiarity of Andra´s Dossier 2005 [Andra, 2005] is that it is based on observations and results from experiments carried out on a real site, namely the Meuse/Haute-Marne laboratory site.

Although more realistic models are available, SCK/CEN intends to continue using a set of conservative calculations to show compliance with the regulatory limits.

There is an agreement that both simple and complex models are complementary for the Safety Case. As stated by IRSN (a regulator) “an approach which balances simplicity, conservatism and realism is likely to be the best starting point for performance assessment”.

11.4.4 Verification and validation of codes

When a model provides results that are used to take important decisions it is necessary to be confident that the model is appropriate, i.e. that it is a good representation of the real system and includes all the relevant processes and geometric details of the system. When possible, the best way to validate a model is to compare the predictions made by the model with observations of the real system. Due to the long time and spatial scales involved in geological disposal, this comparison between model predictions and experimental results can seldom be done.

In the Belgian case of disposal in the Boom Clay, the transport model for non-sorbing tracers has been validated by a large-scale migration experiment. First the model was calibrated using data obtained from a laboratory experiment carried out on a clay core with a length of about 5cm; thereafter, a large-scale in situ migration experiment was carried out from the underground research laboratory. The experiment has been running for more than 20 years and good agreement has been found between predicted and measured tritium oxide concentrations at 1m and 2m from the source, confirming the validity of the calibrated migration model over a scale of a few metres. But even the space scale of this experiment is small compared with the real dimensions of the clay formation: around 100m of thickness and several kilometres in the horizontal direction.

In principle, natural analogues might also be used to validate models: e.g., measurements of natural tracer profiles in clay layers can confirm that the transport in those media is essentially diffusive. However, in most cases the uncertainties in initial and boundary conditions are too high and, consequently, will hinder the use of natural analogues for model validation (SCK/CEN). This is a promising area that deserves further development: if a model can explain the evolution of the formation during the previous millions of years we can be confident in the model predictions for the next million years.

Since strict *validation* of the models used for safety assessments is in most cases impossible, alternative concepts have been introduced in some countries for the process of demonstrating that the models are appropriate. SCK/CEN uses the concept of *model qualification*, which indicates that it has been verified that the model is consistent with the scientific understanding within the assessment basis and that it adequately represents the considered phenomena and interactions.

Andra has co-developed with CEA a simulation platform called ALLIANCES that is used to integrate codes specifically dedicated to the various phenomena (transport, hydraulic, thermal, etc,). The ALLIANCES platform is intended to provide researchers and engineers with a tool to perform a safety assessment that takes into account the specificities of such work, i.e.:

- The requirement to manage very large amounts of data,
- The need to execute complex calculation sequences involving different models,
- A significantly large number of calculations (several thousands of simulations)
- A requirement to control data and results so as to produce specific analyses for each parameter.

For control of computer codes, Andra also had a verification phase of the ALLIANCES platform, in addition to the verification of the individual codes.

British regulations consider that “(model) validation is an iterative and progressive process of *building confidence* (in the models). The measures adopted in a validation programme should include:

- Systematic approaches to model building and consideration of alternative models;

- Iteration between model building, performance assessments and data collection;
- Continuing peer review of model development.

Confidence in the models and codes is increased by application to as many test cases as possible. Typical test cases for model validation are simulation of laboratory experiments and field tests, simulation of paleosystems/natural or anthropogenic analogues and comparison with process level models (GRS-B).

From the contributions received it seems clear that model validation is one of the key issues in the Safety Case. A comprehensive validation programme should be established at the early stages of repository development.

Repository modelling must be based on a solid understanding of the physical and chemical processes and events possibly influencing the evolution of the disposal system and the environmental conditions. A good understanding of the basic processes expected to take place in the repository is fundamental to build confidence in the models created on the basis of such basic processes.

The use of multiple lines of evidence can also play an important role for model qualification: e.g., the model used for transport modelling of retarded radionuclides in the safety evaluations can be underpinned by (1) batch sorption experiments yielding a value of the distribution coefficient K_d, (2) thermodynamic sorption modelling confirming on a theoretical basis the measured K_d value, (3) diffusion or percolation experiments showing that the available sorption sites are effectively accessible for the migrating radionuclides, and (4) underground research laboratory experiments when available..

Verification aims at showing that the computational model correctly implements the intended mathematical model. Verification is far easier than validation and a sensible test plan for the software will usually suffice (NDA). Model verification is often done by comparing the results obtained with two independent solution methods. These can be a comparison of results of a numerical code with an analytical solution or, in the case of complex non-linear models, a comparison of results obtained with two independent numerical codes.

International projects can be useful platforms for code inter-comparison, which is usually not possible on national level, due to a limited accessibility to suitable codes (section 11.6).

11.4.5 Deterministic vs. stochastic modelling.

In general, implementers consider that probabilistic and deterministic calculations are complementary and that both types of calculations are useful for the Safety Case. Many regulators do not show preferences for any particular modelling approach: deterministic or stochastic. However, the wording of UK regulatory guidance, with a risk-based target and the requirement to consider all the situations giving rise to potential exposure to radiation tend to lead to a predominantly stochastic approach. This is also true for US regulations.

Deterministic models are needed to be sure that the real physical phenomena (complex geometries or process couplings) are correctly taken into account (NRG). Simplified models used in the consequence analysis can be deterministic or probabilistic.

In the Netherlands in the 1980´s a first safety assessment was done using deterministic models, while the second safety assessment (done in the 1990´s) used stochastic models. In Spain the initial safety assessments were mainly probabilistic and focused on the consequence analysis while in the more recent assessments more deterministic models are used.

SCK/CEN safety assessments are mainly based on deterministic "best estimate" (or conservative) calculations; this approach is justified by the fact that the considered host clay formation, i.e. the Boom Clay, is very homogeneous (unlike a safety assessment of disposal in granite where the transport modelling through the fractures is inherently stochastic). The deterministic calculations are complemented with stochastic calculations when the influence of the uncertainty in model parameters on an output variable (e.g. dose) has to be evaluated.

As regards the modelling and computation of the scenarios, the approach is also mainly deterministic for Andra. Usually, computation cases are carried out with a given set of fixed parameters. Comparisons are made by changing only one parameter at a time or in any cases with a limited number. In addition to this main deterministic approach, a preliminary probabilistic study has also been carried out in the Dossier 2005 [Andra, 2005], that served as a methodological exercise to illustrate specific sensitivity cases.

GRS-B considers that probabilistic Monte Carlo simulations (simultaneous variation of all parameters) are especially useful to calculate the variability of the results due to parameter uncertainty and to identify the sensitive parameters according to the correlation between parameter value and calculated dose. This approach is preferred to the practice of a deterministic calculation with a “conservative” parameter set because:

- Different processes may compete and compensate each other, so that for many parameters it is not evident which choice is “conservative”
- Combinations of conservative values for several parameters are weighted with their low probability of occurrence
- Sensitive parameters can be identified by their degree of correlation between the parameter value and the calculated dose.
- Probabilistic calculations are especially well suited to deal with parameter uncertainty in a systematic way (NRG). These calculations allow to transmit the uncertainty in the input parameters to the results of the evaluation.

11.4.6 Time scales

Some contributions identify a timeframe of 1 million years for the duration of the calculations done in the safety assessment (NDA, Andra). In the draft of future German regulations [Baltes, 2007] an assessment period of 1 million years is fixed.

11.5 Application and experience

Implementers have been developing and using models for the safety assessment of geological repositories for many years. Regulators are familiar with the safety assessment methodologies too, and in France IRSN has developed and used models to make their independent assessments.

In **Belgium**, during the last 20 years various types of models have been developed and intensively used within the R&D programme, the development of the repository concept and the safety assessments carried out in the framework of the Belgian radioactive waste management programme for the geological disposal of high-level and long-lived radioactive waste. Models and data selected for the most recent safety assessment are described in [ONDRAF, 2001]. The next scientific and technological milestone will be the development of a first “safety and feasibility case” (SFC 1) planned for 2013, that will use updated models and data.

The systematic accumulation and assessment of scientific and technical data for proposal of a design, selection of EBS and safety evaluation of a Deep Geological Repository (DGR) started in the **Czech Republic** in 1993. The results from this period were summarised in 1999 in a “reference design report” and its associated safety assessment [Lietava, 1999], Work has continued and, for instance, multi-pathway biosphere models have been introduced for a generic geological disposal concept [Landa, 2008].

In 2008 RAWRA launched a new project with the aim of updating the reference design of DGR and the safety case. This project should finish in 2011 and include the knowledge acquired since 1997 in Czech R&D projects and foreign DGR development programmes.

In **France**, Andra was entrusted with the task of assessing the feasibility of deep geological disposal in 1991. The search for potential sites was started and in 1996 three applications, backed by preliminary studies and modelling, were filled by Andra for the construction and operation of Underderground Research Laboratories (URL) in granite and clay. The URL in the Meuse and Haute-Marne area (clay) was authorised in 1998, and construction started in 2000.

Andra produced an intermediate report in 2001 for the Project HAVL Argile, the Dossier 2001 Argile [Andra, 2001]. The studies carried out since 1991 were presented in the “Dossier 2005 Argile” [Andra, 2005a] and the “Dossier 2005 Granite” [Andra, 2005b], that included safety assessments. The report for clay included some prelimitary site specific information form the URL while the report for granite was more generic. The wealth of information on the formation produced by the URL will be included in the next safety case, that will be presented in support of the application for the authorisation for the repository foreseen for 2015.

IRSN is a supporting organisation for the French regulator (ASN) with ample experience in modelling. In addition to assessing the technical work made by Andra for the “Dossier 2005 Argile”, IRSN has developed models focussed on the understanding of transient processes, such as chemical and thermal interactions, dehydration/rehydration during excavation and after closure of the repository, and long term behaviour of the Excavation Damaged Zone (EDZ) in indurate clay.

In **Finland,** site identification surveys started in 1983. In 1992 a safety assessment was done on the basis of preliminary site investigations [Vieno, 1992]. A second iteration of the safety case was done in 1999 [Vieno, 1999] using data from the detailed site investigations. Models have continued improving since then and in 2007 a safety assessment was done for the KBS-3H (horizontal) disposal concept at Olkiluooto [Posiva, 2007].

Currently, Posiva is preparing a safety case to support the construction license application for the final disposal facility foreseen for 2012. A new interation of the safety case would be done to support the operation license application in 2018.

In **Germany**, GRS-Braunschweig made a long-term safety assessment for a generic repository with all kinds of waste in rock salt in 1991 [Buhman, 1991]. Since then, models have been under development and more data have become available and are currently being applied in the frame of the licensing applications for real repositories with low and intermediate level waste in Morsleben [Stork, 2004] [Noseck, 2005] and in the Asse mine, both in salt host rock.

In The **Netherlands** the research on radioactive waste disposal started in the early seventies. early 1990´s a generic probabilistic safety analsysis of the Dutch generic reference disposal concept is salt was performed [PROSA, 1993]. The PROSA study was carried forward and extended in the CORA program [CORA, 2001] in which repositories both in salt and clay were investigated.

The extended PROSA method [Grupa, 1999] has been applied to the safety study underlying to the license application for the closure of the Asse salt mine (Germany) including the experimental disposal facilities. If has been used also for a review on behalf of the Ministry of Agriculture and Environment of Sachsen.Anhalt (MLU) of two supporting reports issued in 2002 in preparation of the licensing process for the Morsleben repository for radioactive waste (Endlager für radioaktive Abfälle Morsleben – ERAM) [Grupa, 2003].

In **Spain**, Enresa made a preliminary performance assessment for a repository in granite in 1992, in collaboration with the R&D groups. In the nineties more advanced safety assessments for repositories in granite and clay were done increasingly incorporating the outcome of the R&D program (models, data, ...), complementing the information with bibliographic data or international research and in parallel with the further development of the disposal concept. Later on, some iterations of the safety assessments were done for the repository concepts in granite and in clay.

In **UK** modelling and the corresponding data selection were last done on a site specific basis in 1997 [Nirex, 1997]. Now modelling and data selection are being developed on a generic Disposal System Safety Case (DSSC) that should serve as an input to initial site studies.

11.6 Developments

The developments foreseen by the different organisations are strongly affected by the stage of the national waste disposal programme. Ongoing and future developments are presented in this section.

11.6.1 Implementers

All the implementers that are preparing a new iteration of the Safety Case are developing more advanced models and improving data quality. Here are some examples:

- GRS-B will work on the improvement of the source term models based on actual R&D results (e.g. to include the Si release from the waste matrix, the impact of the Si concentration on the radionuclide mobilisation rates and its transport out of the disposal areas), a consistent and quality assured German thermodynamic database and the impact of climate changes on flow and transport in the overburden and on biosphere processes.
- GRS-B will adapt PA codes to calculate additional indicators, which are currently discussed within the revision of the German safety criteria, to demonstrate the isolation of the waste.
- NRI/RAWRA will concentrate on both development of process models describing processes occurring in a repository and robust models, which use data from these process models. In robust models it is intended to include several source terms expressing high heterogeneity of granite host rock.
- For Andra, the overall modelling strategy will be on a continuing development process in line with the new 2006 French Act and the 2008 revised version of the safety guide. In particular, simulations taking account for knowledge acquisition (including new data on engineered barrier and the site of Meuse/Haute-Marne) will be performed. Andra considers that the modelling strategy is strongly associated to good experimental and characterization programs: quality of data, development of modelling tools for process understanding and development of platform able to integrate the overall data generated by the repository system. In that framework, the development of the ALLIANCES platform will continue.

As noted by SCK/CEN/ONDRAF/NIRAS, in recent years the performance of computers and codes has dramatically increased. This has enabled a significant improvement of the realism of the various computer simulations used within the context of a Safety Case. This trend is expected to continue in the future and reduce the computational limitations of the models used in the Safety Assessment.

Advanced models and computer codes are being developed to represent processes and systems in which more variables are coupled. This coupling means that the models are becoming more non-linear than before, and more coefficients can be made dependent on more variables. As a consequence, further improvements in numerical analysis techniques are desirable.

The recent focus on the safety functions of the barriers adopted by several implementers can affect the modelling approach too.

When a potential site becomes available, the modelling strategy of the implementers becomes determined by the features of the geology in that area. The selection of a site enables switching from generic studies to more realistic site-specific studies and models, as in the cases of Andra and Posiva.

In the future it is expected that more effort will be spent in the documentation of the models and data used in the Safety Assessment. For instance, in Finland the implementer (Posiva) foresees that in the next step, a major implementation is the collection of Models and Data used in the Safety Case to be published as a report in its own right. The *Models and Data Report* will act as an interface between the safety case activities and the principal supporting activities. The information included in the *Models and Data Report* is selected on the basis of its safety relevance: the EBS and site data that directly provide the input to the safety case are discussed in these reports, while more details can be found in the supporting background reports, such as the Site Descriptive Model report and various technical descriptions of the engineered barrier system. The quality of the Site Descriptive Model report is mainly ensured by the application of scientific principles, while the methods of quality control for the technical barrier design and implementation depend on the nature of the materials and technology in question. The *Models and Data Report* captures the most significant information related to safety, the quality of which is of primary importance for confidence in long-term safety.

In addition to the national developments on modelling, international collaboration can be useful. An example is the work developed within the Component 4 of PAMINA Project “Relevance of Sophisticated Approaches in Practical Cases”, whose objective was to evaluate whether using more complex and realistic modelling approaches in the Safety Assessment is necessary or useful. This Component 4, directly related to repository modelling, has generated information applicable to repository modelling in the Safety Assessment.

International benchmark or code inter-comparison exercises are identified as fundamental for the validation/verification of the models and codes used in the different national programmes. Collaboration between the different countries will reduce the workload of each organisation, eliminating the need of implementing several codes for the same calculations in a given organisation.

Deterministic and probabilistic models and calculations are seen as complementary by most organisations and both will be used in future Safety Cases. Very simplified models or analytical solutions can be useful too for communicating results to different audiences and showing system understanding. Different models or sets of data can be used to obtain realistic, conservative or overly pessimistic estimates for a given scenario. In general, implementers remain open minded to use all the previous classes of models and calculations within the Safety Cases if they are considered useful.

11.6.2 Regulators

Some countries (France and Finland) already have detailed regulations that provide broad guidance and requirements on how the implementer should model the disposal system. Other countries (such as Belgium and Germany) are in the process of developing their own detailed regulations that will include guidance and requirements on modelling. There is a general trend of moving from generic regulations (focused on a dose/risk limit for the disposal facility) to more detailed regulations that establish requirements and provide guidance on the different aspects of repository development, when a national disposal programme moves from the phase of conceptual studies to more advanced phases of site selection and detailed design of the facilities.

Open discussion between implementers and regulators is very useful from the initial stages of the development of a repository. For the implementers it is particularly useful to have guidance on regulators expectations.

On the basis of Bel V, IRSN and GRS-K contributions, the following topics are expected to draw particular attention of the regulators in the future:

- Scope and objectives in the Safety Case framework of various (“reference”, “altered”, “what if”, …) scenarios. Contributions of the different conceptual models to the global safety assessment.
- Justifications (e.g. by using conservative assumptions) for decomposing model in sub-models according to several time frames, space domains and/or physical processes and the necessary simplifications.
- Justification that all important features, events and processes of the repository system are considered in the models. Provide evidence for the scientific understanding of the relevant (and prospectively relevant) processes.
- Verification, validation and confidence building of the models and codes according to the state of the art in science and technology. The applicability of the models has to be substantiated, e.g. by means of natural analogues, experiments, in-situ tests and reviews.
- Quality assurance procedures implemented for developing the models and generating the data to be used in the Safety Assessment. Proper documentation and traceability of the process of model generation.
- Treatment of uncertainties. Where uncertainties exist at a conceptual level, alternative models have to be discussed and, if necessary, to be used. The robustness of the system against model uncertainties should be demonstrated.
- Treatment of the host rock heterogeneity and up-scaling. The relevance of this topic is strongly rock-specific.
- Easiness of interpretation of global assessment results: particular attention is the case of complex safety assessment results (e.g. stochastic approach).

11.7 Conclusions

During the workshop fruitful discussions on modelling strategies were held. The conclusions of these discussions are summarised in this section.

Types of models used in the Safety Case.

Although the terminology used can be different, there are great similarities in the different types of models used by the different contributors:

- On the basis of their objective two types of models are used: models to predict the evolution of the repository and models for the consequence analysis (release and transport of radionuclides and radiological consequences).
- On the basis of the part of the repository involved two types of models are used: detailed models to characterise the evolution of sub-systems or to generate input data for the integrated models (component models) and integrated models to perform consequence analysis for selected scenarios.

Very detailed process level models usually are not included explicitly in the Safety Assessment, but they provide the basic knowledge and data needed to generate the Safety Assessment models and can be used to support the additional arguments included in the Safety Case.

Most contributors agree with the hierarchy of models presented in Figure 16, with the exception of Posiva and in some way Andra. Posiva highlights that they do not apply it since the system model would be, for practical limitations, unavoidably inadequate to describe the variety of important processes in the repository system. When going from one level of models to the next (higher) level the degree of detail of the models decreases (simplifications are included) .

The modelling strategy is top-down while the modelling process is bottom-up.

Model validation/verification

Validation and verification of the models used in the Safety Assessment are considered very important topics by all the contributors.

Verification of the computational models can be done in the usual way through comparison with analytical solutions and inter-comparison between different computer codes. International benchmark exercises can be very useful for all the organizations involved.

Validation of models is usually undertaken through comparison of model predictions with experimental observations. There is an agreement that strict validation of the models used for spent fuel and HLW repositories is not possible, due to the long time periods involved. Alternative broader concepts are introduced by some organisations: SCK/CEN-ONDRAF/NIRAS talks about “model qualification” and NDA aims to “build confidence” in the model, using all the means available.

The validation/qualification of the "phenomenological" process level models and component models for very long term predictions is a very complex task. Validation/qualification of the "simplified SA" sub-models used in the "top level model" could be done by comparison with the detailed process level and component models, previously validated.

Stochastic/deterministic approaches

Deterministic and probabilistic calculations are seen as complementary by most organisations. Some organisations include both classes of calculations when making a Safety Case.

Deterministic calculations are better for very detailed calculations, system understanding and communication purposes. Stochastic calculations are particularly appropriate in dealing with parameter uncertainty, and stochastic sensitivity analyses provide much information on the key parameters controlling the repository behaviour.

Simplifications in the models

Simplifications are always made when modelling a complex system, such as a geological repository for radioactive wastes. The simplifications carried out must be documented and their validity must be justified. In general, a simplification is valid if it is conservative but does not produce a gross overestimation of the negative effects.

As stated by IRSN (a regulator) "an approach that balances simplicity, conservatism and realism is likely to be the best starting point for PA modelling". This assertion is valid not only for early iterations of the Safety Case but even for the last iteration.

It is expected that in successive iterations of the Safety Case more realistic models would be introduced and the degree of conservatism would decrease, according to the progress of knowledge (site, experiments,…). As a consequence, it can be expected that doses will decrease (or remain constant) in the successive versions of the Safety Case. If this is the case, it would be a good argument to support the fact that the whole process of repository development has steadily improved the quality of the disposal system and the safety assessment.

Although the degree of realism of the models is expected to increase, it is quite common to use a set of conservative simplified calculations to show compliance with regulatory limits (as SCK/CEN-ONDRAF/NIRAS intends to do).

For probabilistic calculations there is a need for additional model simplifications in order to limit computer runtime to allow several hundreds or thousands of individual calculations to be carried out within a reasonable timeframe.

Very simplified models (such as analytical solutions) can be included in the Safety Case to demonstrate proper understanding of a complex system and for communication purposes. If the results obtained using a complex model with many parameters can be reproduced using a simple model with a few parameters it is clear that the key processes and parameters (those included in the simplified model) have been identified and the complex system is well understood. This would be a strong argument in the Safety Case.

Quality Assurance and documentation

Since the development of a repository from initial studies to its closure can take several decades and involve many organisations and individuals, it is necessary to establish a QA programme from the start of the project. A well established QA programme is considered fundamental by all the organisations, both implementers and regulators.

The whole process of model generation must be undertaken following appropriate QA procedures and be properly documented, including the decisions taken during the generation of the model (and the reasons behind them) and the simplifications done (and their justification).

The generation of the data to be used in the models is a topic closely related to the model generation, and must be done following similar QA and documentation standards.

Ideally, the capability to run old computer codes should be maintained during a significant period of time (decades at least). But codes evolve (new versions are released) and might also be replaced by new ones. When updating the codes or changing into a new one, it is very useful to run older simulations with the new version/code and perform a benchmarking of the old and new codes, and document it properly. If a new code provides the same or very similar results than the old one for a set of typical problems, the need to use old codes is reduced or eliminated, although their maintenance could be required by the regulators.

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12. Criteria for input and data selection

12.1 Introduction

The development of a repository is a long process that requires decades to complete. During this period a great amount of data will be generated, mainly in the areas of waste characterisation, site characterisation and supporting scientific studies to understand the basic processes that control repository evolution and radionuclide transport. Proper generation and handling of these data are critical for the development of a robust Safety Case.

Due to the important role of modelling in the development of a Safety Case, the generation of the quantitative data required by these models is a critical topic, that needs to be explicitly addressed.

This Chapter presents the approaches followed by the organisations responsible for developing a repository (implementers) for generating and handling data for the Safety Case and the expectations of regulators on this topic. It is focussed on the methodology followed to produce and select the data used in the Safety Case, not on describing the data used. Some contributions provide detailed descriptions of the data used, in addition to the strategy followed for generate and select such data. These examples of the data required by a Safety Case are not discussed here, but can be found in the Appendices.

12.2 Regulations and Guidelines

In IAEA Safety Standards for geological disposal [IAEA, 2006] there are several paragraphs dealing with the data generation and data use in the development of a geological disposal facility:

- "The step by step approach (to develop a safe repository) involves: the ordered accumulation and assessment of the necessary scientific and technical data: the evaluation of possible sites; the development of disposal concepts; iterative studies for design and safety assessment with progressively improving data;…."
- "The operator is also responsible for carrying out all the necessary investigations of the site or sites and of materials and for assessing their suitability, and for providing data for safety assessments".
- "An understanding of the performance of the disposal system and its safety features and processes evolves as more data are accumulated and scientific knowledge is developed. Early in the development of the concept, the data and the level of understanding gained should provide the confidence necessary to commit the resources for further investigations…"
    - "As site investigation progress, safety assessments become increasingly refined, and at the end of a site investigation sufficient data will be available for a complete assessment. Safety assessments also identify any significant deficiencies in scientific understanding, data or analysis that might affect the results presented".

- "A safety assessment in support of the safety case is performed and updated throughout the development and operation of the geological disposal facility and as more refined data become available."
- "Justification and traceability both require a well documented record of the decisions made and the assumptions made in the development and operation of a geological disposal facility, and of the models and data used in arriving at a particular set of results for the safety assessments".
- "The management system and the supporting QA programme for the geological disposal facility will provide for the production and retention of documentary evidence to illustrate that the necessary quality of data has been achieved;…"

The ideas expressed in these paragraphs summarise the main expectations of the regulators regarding data generation and use in the development of a repository.

In some countries, such as Spain and The Netherlands, no detailed regulations have been developed for deep geological repositories, and no specific requirements or guidelines are available on the topic of data generation within the project and data selection for models.

Other countries, with geological disposal programmes at more advanced stages, already have regulations (at least in draft form) or discussions between the implementers and the regulators that provide information on the expectations of the regulators regarding the selection of data to be used in a Safety Case. In the next sections the information gathered regarding regulations and guidelines from the regulators is presented on a country basis.

Belgium (SCK/CEN-ONDRAF/NIRAS): Regulatory requirements and guidelines concerning long-term safety of high-level radioactive waste disposal are still in preparation in Belgium.

The Belgian regulator (FANC-Bel V) requests the use of "best estimate" values of the parameters in the analysis of the performance of the barriers and "conservative" values in the analysis of the radiological consequences.

Czech Republic (NRI, RAWRA): According to guides of the Czech regulator SUJB, safety reports must contain data describing comprehensively all components of site and Deep Geological Repository (DGR) design (topography, geology, hydrology, geochemistry, demography, design of repository, waste packages, etc.). Primarily the following data are needed to judge criteria for siting according to Degree of SUJB 215/2007 e.g.:

- The occurrence of karstic phenomena in the extent endangering the stability of the rock massif in the bedrock and in the rock cover of the land selected for the siting.
- The manifestation of post-volcanic activity such as the escapes of gases, thermal, mineral and mineralised waters, found on the lands or area of the supposed siting and in their site vicinity zones.
- The achievement or exceeding of the value of intensity of the maximum calculated earthquake 8°MSK (scale of Medvedev-Sponheuer-Karnik for estimation of the macroseismic effects of earthquakes) on the lands of supposed siting.

- The occurrence of the capable and seismogenic faults with the recent surface deformations of area and with the possibility of origination of secondary faults, found by a geological survey on the land of supposed siting.

All the data needed for evaluation of impact of radionuclides on the environment must be gathered. Modelling of transport of radionuclides shall be based on detailed knowledge of site for DGR. A list of parameters, their substantiation a possible change of parameters in space and time and their maximal and minimal values must be given. A list of reports with data and information not directly given in the safety report must be included at the end of safety report and must be given their availability.

Finland (Posiva): The Finnish Regulatory Body (STUK) states about modelling and input data that “In accordance with Section 29 of the Government Decision, the computational methods shall be selected on the basis that the results of the safety analysis, with high degree of certainty, overestimate the radiation exposure or radioactive release likely to occur” [STUK, 2001].

From the conceptual models, drawn up to describe the physical phenomena and processes affecting the performance of each barrier, the respective calculation models are derived, normally with simplifications. Simplification of the models as well as the determination of input data for them shall be based on the principle that the performance of any barrier will not be overestimated but neither overly underestimated.

The modelling and determination of input data shall be based on the best available experimental knowledge and expert judgement obtained through laboratory experiments, geological investigation and evidence from natural analogues.

The models and input data shall be appropriate to the scenario, assessment period and disposal system of interest. The various models and input data shall be mutually consistent, apart from cases where just the simplifications in modelling or the aim of avoiding the overestimation of the performance of barriers implies apparent inconsistency.

France (Andra and IRSN): The RFS.III.2.f of 1991 [JORF, 1991], which was the reference for the Dossier 2005 Argile [Andra, 2005], recommended in section [4] *“5.4. Modelling …. Considering the importance of the modelling, particular care must be taken in the validity of the models and the data.”*. It also rules the type waste to take account for (as input data): [4] *“The installation of radioactive waste disposal in deep geologic formation is conceived to receive the ultimate radioactive waste which, after their storing, cannot for reasons of safety or radioprotection be stored on surface or in shallow depth. It can involve in particular:*

- *Waste of average activity (based on mass) containing radionuclides of long period. Their quantity is such that it would not allow their storage, either in an installation of surface weak activity short half-life storage, nor in an installation of weak activity and long half-life storage,*

[4] To Note: not an official translation

- *Waste of high activity (based on mass) containing significant quantities of radionuclides of long period. This waste mainly arises from the reprocessing of the used fuel and are characterized by an important release of heat,*
- *Used fuels which would not be reprocessed."*

The revised version of this safety rule issued in 2008 [ASN, 2008] includes some specific recommendations about data selection: *…." Considering the importance of the modelling, a particular care must be taken in the quality of the data…"…" Considering the iterative character of the demonstration of safety, the level of detail of the modelling will also depend on the progress of the studies and on the level of precision of the data which will have been collected at the time of the modelling*"(not official translation).

Germany (GRS-K and GRS-B): At present, no legal regulation exists in Germany which demands a specific data selection in the framework of a safety case (SC) respectively safety assessment (SA). Only general requirements for input and data selection are mentioned for the safety case, the safety analysis and its review:

- "During exploration, the applicant shall ascertain the principal site data relating to safety of the repository in an adequate level of detail as required for the safety cases. Where this requires the quantitative determination of site data, the accuracy / range of and any potential changes in such site data under emplacement conditions should be ascertained. The applicant must prove the validity of such data to the licensing authority. Where data obtained from other sites is to be used, the transferability of such data must be justified."
- "For long-term forecasts, where applicable, reference data and reference models should be used for periods during which the uncertainty of the input data and calculation models is so high as to cast doubt on the validity of the results. Qualitative evidence should additionally be used for such periods".
- "Deterministic calculations should be based on as realistic as possible modelling (e.g. by use of median values as input parameters".
- "In order to review the safety assessments for emplacement operations, decommissioning and the post-closure period, a measurement programme should be carried out which can be used to analyse the input data, assumptions and statements of these safety assessments. In particular, this measurement programme should record the impacts of thermo mechanical rock reactions to heat-generating waste, geotechnical measures, and rock-mechanical operations. For evidence purposes, such measurements should continue to include the initial status and the development of activity concentration in spring water and groundwater, soil, water bodies and the air within the repository's sphere of influence. Significant deviations from the relevant data, statements and assumptions in the cited safety cases should be notified to the competent authority immediately, and evaluated with regard to their safety relevance. If necessary, counteractive measures should be carried out by the operator in order to avoid any impairment to important safety functions. Where approval is needed for such counteractive measures, this should be obtained by applying to the competent

authority. The competent authority shall also decide on discontinuation of the measurement programme.”

Netherlands (NRG):There are presently no Dutch regulatory requirements and provisions that directly relate to the topic of “data selection”. Indirectly however several laws regulate the protection of the public against hazardous materials. For example, with regard to nuclear energy, the purpose of the Nuclear Energy Act [DG 63] is to regulate (Article 15b) the protection of people, animals , plants and properties. In addition a number of decrees have been issued containing additional regulations.

United Kingdom (NDA): Relevant agencies have published guidance, known as the GRA [EA, 1997], which outlines how an application for land based disposal of solid radioactive waste would be judged. A revised version of the GRA was published in February 2009 [EA, 2009].

In terms of specific recommendations on data, the GRA requires assurance of the adequacy of a developer's proposals for collecting information and data to support a decision to start underground operations and to support a decision to move to each stage of development. The GRA outlines requirements for the developer to have procedures for documentation and record keeping, quality management of data, and to be alert to possible future changes to standards and to basic data. In circumstances where there is uncertainty due to lack of relevant data it recommends the use of expert judgement and states that where “*few or no relevant data can be gathered, a 'stylised ' approach may be adopted, in which arbitrary assumptions are made that are plausible and internally consistent but tend to err on the side of conservatism*”.

12.2.1 Relevant topics

From the previous regulations and guidelines some important topics can be identified:

- The implementer is responsible for carrying out all the necessary investigations of the site or sites and of materials and for assessing their suitability, and for providing data for safety assessments.
- Regulations may consider the “waste” as an input and, as a consequence, contain instructions relative to the type of waste to take into account in design and associated safety approach to consider (Andra).
- Regulations usually do not contain detailed instructions on how to select the data to be used in the Safety Case. Only in UK there exists a recommendation of using expert judgement in circumstances where there is uncertainty due to lack of relevant data.
- The data available for the Safety Case is expected to improve along the development of a repository. In early stages generic data can be used in the Safety Case while in later stages more site specific data will be available (all).
- The degree of detail and completeness of the data used in a Safety Case must be consistent with the purpose of the Safety Case.

- Models and data used should try to be realistic (GRS-K), and should not lead to a gross underestimation of the performance of a barrier (Posiva).
- One regulator (FANC-Bel V) requests the use of "best estimate" values of the parameters in the analysis of the performance of the barriers and "conservative" values in the analysis of the radiological consequences.
- Model development and the generation of data to be used in the models are closely related topics. The quality of the data used in the models must be justified (Andra, IRSN, Posiva).
- Data generation and selection must be done following established quality assurance procedures (GRS-K, NDA) and the process of model and data generation must be properly documented. Transparency and traceability of the whole process of data selection are key requirements.

12.3 Terminology

Most participants have adopted the terminology used in the IAEA glossary [IAEA, 2007] and other international references. In general, the introduction of "new" terminology is avoided (NDA).

In the methodology under development in Belgium for the next Safety Case, the assessment basis group expresses parameter data under the form of a source range and an expert range defined as:

- <u>Source range</u> of a parameter is the range of values outside of which the parameter value is unlikely to lie, considering the current knowledge.
- <u>Expert range</u> of a parameter is the range of values within which experts expect the parameter value to lie; the expert range is thus a subset of the source range.

Andra introduced some specific terminology in its Dossier 2005 [Andra, 2005] for data selection: phenomenological, conservative or pessimistic values of parameters.

12.4 Methodology

The analysis of the contributions received shows a common view on the generation and selection of data necessary to develop and demonstrate the safety of a deep geological repository.

12.4.1 General methodology

Laboratory and in-situ experiments generate data for short duration experiments under a given set of conditions (temperature, pressure, water composition,…). The applicability of the data generated in the far future under different conditions (that evolve with time) is a critical topic that needs to be addressed explicitly when selecting input data for the models (Enresa).

In order to select input data for the long term modelling it is necessary to have a good scientific understanding of the basic processes expected to take place in the repository and their potential effects on the barriers and the relevant parameters.

Input data must be developed on the basis of the best available scientific and technical knowledge (Posiva, GRS-K and Andra). The whole process of data generation must be undertaken following quality assurance procedures, and must be properly documented.

Safety Cases are prepared at selected decision points in the repository development programme (depending on the regulatory requirements). The degree of detail of the models and the quality of the corresponding data used must be consistent with the objective of the Safety Case.

The models and data will evolve along the repository development, but it is important to follow a frozen modelling strategy and use frozen models and data in each iteration of the Safety Case, to ensure transparency and traceability. In each iteration the possible model improvements and data needs for the next step should be clearly identified and documented (Bel V).

Independent reviews of the data selected for the Safety Case are important to ensure the proper quality of the data. The need for independent review of the data increases with the successive stages of repository development: while early iterations of the Safety Cases can be done without external review, later iterations for site selection or repository construction applications should include independent reviews of the data selected.

In France (Andra), a peculiar attention was paid in the Dossier 2005 Argile [Andra, 2005] to the basic input data which includes two main aspects: the radiological inventory model and site characterisation. They were presented in specific documents. Andra considers that any repository development project must start with an analysis of the technical input data on which it is based. The number and variety of these data increase with each iteration of the repository's definition process. The input data and the fruit of the analyses conducted under the Dossier 2005 are structured into a documentary architecture organised according to the safety approach.

12.4.2 Site characterisation

Site characterisation and the development of a good understanding of the main properties of the host formation is one of the most challenging tasks in the development of a safety repository. Due to the great amount of raw data that will be produced and the numerous organisations that will be involved, site characterisation requires a specific data management strategy to ensure that the whole process is done following the highest standards.

12.4.2.1 Initial stages

In the initial phases of a repository program, when no site has been selected or site specific data are scarce, Safety Assessments can be done on the basis of generic geosphere data (GRS-B, Enresa, NRG, NRI and NDA). These preliminary safety assessments can provide useful guidance for the site characterisation.

In repository projects it was aspired to firstly achieve a largely comprehensive data set to have the basis available for a site specific safety assessment. The recent development appears to tend towards a partly interchange in the sequence of data collection and safety assessment. Instead to firstly trying to collect a data set which should be as comprehensive as possible, a safety assessment is already required in an early project phase regardless of the current grade of completeness of the collected geological data set. Those data, which are needed to be fed into the safety assessment but which are still to be determined, have to be soundly estimated for the safety assessment and reasonably varied. The benefit from the early safety assessment, before exploration is completed, is to be aware of the significance of the different geological data for the safety and furthermore the knowledge, with which degree of exactness the geological data have to be explored (GRS-K).

As the site and design for a geological disposal facility in the UK have not yet been chosen, the NDA is currently developing a “generic” safety case to support the different stages in the implementation of a geological disposal facility. As the assessing of specific sites starts, NDA will be able to refine the approach to include site-specific parameters.

Enresa safety assessment exercises have been done for synthetic sites, created on the basis of the limited data available for Spanish favourable areas. As a consequence, the detailed data that will be generated during the site characterisation phase were not available, and only generic, but plausible, sites have been analysed. Similarly, NRG has performed several Safety Assessments using generic data representative of the conditions met in the underground and biosphere in the Netherlands.

12.4.2.2 Detailed site characterisation

Site characterisation will generate a great amount of raw data that must be processed, interpreted and integrated in order to develop a good understanding of the site. The ideas presented in this section on how to carry on the site characterisation process have been provided mainly by NDA but are representative for other countries.

For NDA the process of site characterisation is comprised of five inter-related stages:

- Data acquisition – to obtain measurements and to collect data utilising a range of measurement techniques and surveys;
- Data processing – to transform measurement data into information that is meaningful in terms of the properties of the site;
- Interpretation – to understand the significance of that information in terms of the individual aspects of the site (e.g. groundwater flow, geology, environmental processes, etc);
- Integration – to develop a self consistent understanding of the site as a whole which includes all the individual aspects;
- Communication – to communicate the understanding obtained to others (e.g. those involved in performance assessment, engineering design and key stakeholders) and to obtain feedback that could influence the ongoing process of site characterisation.

For GRS-B/DBETEC/BGR the process of site characterisation consists of five steps: data review, data acquisition, interpretation, data matching and the prediction for future variability.

For Andra one of the first steps is to define the expected functions of the geological medium. In coherence with the regulations, and the assigned safety functions, the research work on clay aims at designing a deep repository, and ensuring the good performance of the host formation. Acquiring knowledge of the host formation and surrounding formations was organised by pursuing several complementary strategies including the work carried out in the underground laboratories located in the selected site (Meuse/Haute-Marne Laboratory) or in other clay formation (Mont Terri Laboratory in Switzerland).

The overall site characterisation will be carried out in a series of stages. At discrete, pre-determined stages during the investigations there are 'data freezes' at which stage the interpretation activities commence followed by engineering design and safety assessment studies. However, during this time further investigations are progressing. At the next data freeze further information is fed into the interpretation, design and safety assessment teams such that they can maintain a rolling programme of work. Monitoring the progressive development of the engineering design and safety assessment through the stages following each of the data freezes may provide a means of evaluating progress towards completion of the surface-based investigations.

The process of site characterisation is usually undertaken by the development and progressive updating of a series of discipline based 'Site Descriptive Models'. The descriptive models are a convenient means for interpreting and presenting the results of investigations at a site. The various descriptive models do not exist in isolation and there is transfer of information between models. The descriptive models are also used as input to the performance assessment models and engineering designs for the facility at the site. The descriptive models that may be developed for a site are likely to include the following: geology, hydrogeology, hydrochemistry, geotechnical, transport properties, thermal properties and biosphere

The geology model provides the framework on which all the other models are built because it gives a basic understanding of the nature and distribution of the various rocks and soils that are present at the site.

Descriptive models may change significantly as new information on and understanding of site characteristics is obtained. However, as understanding develops during the later stages of the investigations, it is anticipated that the descriptive models will become stable and not change significantly as further information is obtained. Hence, the stability of site descriptive models is also a potential criterion for defining completion of the surface-based investigations.

12.4.3 Waste characterisation

Some organisations (Andra and NDA) foresee that many different wastes will be disposed of in the repository, and for them waste characterisation (determination of radionuclide inventory and waste properties) is a complex topic that requires an effort similar to site characterisation. Handling the great amount of data generated in the waste characterisation requires a specific strategy. The rest of participants consider only spent fuel or HLW in their assessments, and waste characterisation is simpler.

In France (Andra) the waste is described in terms of typology, radiological contents and physico-chemical characteristics in a specific document associated with the Dossier 2005 Argile [Andra, 2005]. As input to the repository feasibility study, this inventory model allows for both *the waste already produced*, that is stored in conditioned and unconditioned form on the production sites and *the waste that will be produced in the future by the current nuclear power plants.* This dimensioning inventory model provides an envelope of volume and nature of the waste likely to be considered, in order to assess its geological disposal feasibility with dimensioning margins.

In coherence with the guidance, deep geological disposal concerns two categories of waste: the high-level waste (or vitrified waste) and the intermediate-level, long-lived waste.

The characteristics of the waste considered for the storage are a function of scenarios of envisaged reprocessing and conditioning. Four scenarios were defined in collaboration with the producers, in order to examine how repository architecture could adapt to the various management processes for the electro-nuclear fuel cycle (but they did not predict an industrial blueprint). In the Dossier 2005 the evaluation was based on two envelope scenarios.

12.4.4 Sources used for data generation

The main sources used by the contributors to generate input data for the Safety Case are laboratory experiments, in-situ experiments, natural analogues, modelling and calculation, expert elicitation and bibliography.

Laboratory experiments allow studying the processes taking place in the repository under well controlled conditions, to understand the basic processes taking place in the repository and measure parameter values.

In situ experiments allow obtaining data under more realistic conditions and at a larger spatial scale compared with laboratory experiments, although at a higher economic cost. Even in-situ experiment will be limited compared with the real dimensions of the repository and the formation and timeframe of the evolution of the disposal system.

In theory, natural analogues can be used both to validate models and generate data valid in the very long term. However, in many cases the uncertainties in initial and boundary conditions are too high and, consequently, will hinder the use of natural analogues for data generation. Natural analogues are expected to be especially useful as supporting arguments for the Safety Case, while its usefulness for data generation would be mainly through comparison with the data generated by other means (laboratory or in situ experiments) to increase the confidence on the data selected.

A great number of process level models (that can be quite complex) are developed and used by R&D groups in order to reach a good scientific understanding of (and identify the basic processes that control) a limited part of the disposal system evolution. Many of these models usually are not included explicitly in the safety assessment, but their results are used to build the models used in the safety assessment, generate data for them or support the data selected by other means. An example is the Thermodynamic Sorption Models (TSM) developed to understand sorption processes on solids (bentonite, clay or granite). These TSMs are not included explicitly in the safety assessment but are used to justify the simplified models (use of distribution coefficients Kd to represent sorption) and the parameter values (Kd values) used in the safety assessment. The justification of the validity of the data generated using these process models relies on the validation of the process level models and codes used. Another example is the Thermodynamic Data Base (TDB) developed to understand the radionuclide behaviour in solutions (Andra).

Expert elicitation can be used to assess the uncertainties about events and variables when the source of uncertainty is lack of knowledge (epistemic uncertainty). Expert elicitation is a complex and time consuming process and most contributors do little or no use of it. Only NDA strongly relies on expert elicitation for generating data for the safety assessment.

Bibliographic data can be used extensively as long as its applicability to a particular disposal concept and site can be justified.

12.4.5 The role of the sensitivity analysis in the selection of input data

There is an agreement that the sensitivity analyses from previous Safety Assessments are a useful tool to identify the parameters with high/low relevance for the model and prioritize the efforts of the input data selection process. The effort devoted to the determination of the value or range of values of a given parameter should be proportional to its influence on the results of the model where it is used. Nevertheless, if the models and/or parameters of the new iteration of the Safety Assessment differ form the previous ones (as probably will be the case), the conclusions from previous sensitivity analyses could be not totally applicable (and should be reviewed to include a reduction of uncertainty, for instance).

In the first iteration of the Safety Case no previous sensitivity analysis is available, and a review of the assessments done by other organisations can be used instead.

Posiva intends to include in the “Models and Data Report” (section 11.4.6) information on the impact of the parameter on assessment results, including any sensitivity analysis or bounding calculations that may have been performed to evaluate how the system evolution and ultimately the radiological consequences are affected by the data at hand.

Sensitivity analysis is an important tool of the Safety Assessment.

12.4.6 Expert elicitation

Expert elicitation has been used during roughly the last seventy years in different areas of science, technology, weather forecasting, strategic planning, economy and many other fields as a reasonable way to assess uncertainties about events and variables when the source of uncertainty is lack of knowledge (epistemic uncertainty)

During the development of a Safety Case in general, and in the selection of data values for the assessment in particular, a great amount of expert judgement is involved. The safety assessment experts and the supporting specialists must take many decisions during the selection of parameter values, and these decisions must be justified and documented.

In the Czech case (NRI) the main tool of obtaining data was informal expert judgement from subject experts. Generalists from the coordination group identified the issues and tasks related with safety analysis of a repository.

Most implementers do little or no use of expert elicitation to aid the selection of appropriate data used in the safety assessment. Only NDA uses expert elicitation to generate the probability distribution functions for all the uncertain parameters. Posiva uses expert elicitation only for very uncertain parameters, such as the element solubility.

Expert elicitation is seen by most organisations as the last resort to generate input for the safety case, to be used only when more conventional ways to accomplish the task are not applicable.

12.4.7 Definition of probability distribution functions for stochastic calculations.

One of the advantages of probabilistic calculations is that the parameters uncertainty is explicitly taken into account in the calculations and the uncertainty in the input parameters is propagated to the output result (usually the dose). But assigning probability distribution functions to the parameters used in the calculations is not straightforward.

On the basis of the experience gained in previous iterations of the Safety Case it is possible to identify that only a few parameters control the repository behaviour. The uncertainties affecting these relevant parameters must be identified during the process of data selection. These uncertainties will be the basis to define the probability distribution functions to be used in the stochastic calculations. For other less important parameters broad probability distributions can be appropriate.

The methodology used by SCK/CEN/ONDRAF·NIRAS in SAFIR 2 [ONDRAF, 2001] is representative of the pragmatic approach usually followed by the implementers to derive the pdf´s for uncertain parameters:

- On the basis of the available data sets the experts estimate a minimum and a maximum value for the parameter of interest.
- When the range of possible values was larger than a factor 5 a logarithmic distribution is adopted. If the range is smaller than a factor 5, a linear distribution is used.
- If it was considered necessary to give a higher statistical weight to a particular region of values (around the best estimate value, for instance), a (log)triangular distribution is selected. When this is not considered necessary, i.e. the real value is expected to be somewhere between the minimum and maximum, a (log)uniform distribution was selected.

Enresa has followed a similar approach in the definition of the pdf´s for stochastic parameters: if the range of potential values covered one order of magnitude or more, logarithmic distributions were implemented while linear distributions were used when the uncertainty was smaller than a factor 10. Solubility limits are examples of the first class of parameters and the instant release fractions of the inventory are examples of the second.

For probabilistic calculations usually triangular distributions, i.e. minimum, best estimate and maximum are used by NRI.

12.4.8 Selection of parameter values for deterministic calculations

For deterministic calculations typically two different classes of parameter values are selected: “best estimate” and “conservative” values.

During the generation of input data in SAFIR-2 project (ONDRAF·NIRAS/ SCK/CEN) experts were requested to provide “best estimate” values of the parameters. It was found that the “best estimate” values selected by the experts and the safety assessors tended to lie systematically on the conservative side and were not always representative of the best estimation of the parameter. This resulted in a loss of information regarding the “true” value expected for a particular process.

The Belgian regulator (FANC-Bel V) requests the use of “best estimate” values of the parameters in the analysis of the performance of the barriers and “conservative” values in the analysis of the radiological consequences.

Andra (France) uses a classification of data values based on the degree of knowledge acquired on phenomenon or data: “best estimate”, “conservative”, “pessimistic or penalising” and “alternative” values.

A “pessimistic or penalising” value designates a value that is not based on phenomenological understanding, however empirical, but that definitely overestimates the repository impact. These values can be used in scoping calculations with the purpose of bounding potential effects.

An “alternative” value stands for a value that can not be classified according to the three previous items. This category covers values that appear to be more realistic than the selected best estimate but have been less thoroughly validated.

In France (IRSN) best estimate values are used in low likelihood scenarios (altered evolution scenarios due to low likelihood events) while conservative values are used for normal evolution scenarios.

In Czech Republic conservative, best estimate values or ranges of values are used in the deterministic calculations (NRI).

Andra, ONDRAF·NIRAS/ SCK/CEN and Enresa consider useful to generate both “best estimate” and “conservative” values of the parameters to be used in different sets of calculations. This would reduce the tendency of the experts to be conservative when selecting “best estimate” values. The comparison of the results of the two sets of calculations (best estimate and conservative) provides an indication of the margin of improvement of the calculated performance of the repository if the uncertainties leading to the conservative values are reduced.

In the Netherlands, a principal criterion for the selection of model data that has been applied in the VEOS, PROSA and CORA studies was that the data must be generic, but representative of the conditions that are met in the underground and the biosphere of the Netherlands.

In Germany the draft of a new regulation (GRS-K) specifies that deterministic calculations should be based on as realistic as possible modelling (e.g. by use of median values as input parameters).

In general, most organisations perform the deterministic calculations using “best estimate” values for the parameters.

12.4.9 Quality Assurance

There is an agreement in the need for a comprehensive Quality Assurance system to cover all the activities concerning the development of a deep geological repository, including data gathering. The quality assurance system and quality assurance programmes must be documented before the start of relevant activities. All organizations participating in the development of deep geological repository must have established a quality assurance system (NRI).

The QA programme to ensure data quality should put special emphasis on transparency, traceability, external review and proper documentation.

A quality plan must be prepared to cover all activities related to the site characterisation programme. The intended use of the data will be documented as part of the planning; other uses of the data will be evaluated and justified. The quality plan will assure the compatibility of data derived from scientific investigations with any conceptual or mathematical models. The quality plan will also establish provisions for the evaluation of data quality to assure that the data generated are, as far as possible, complete, representative and accurate. Uncertainties in data and their analyses will be identified and documented. A data management system will be planned in advance of characterisation activities to ensure the highest standards of data access and storage. Peer reviews of methods and documentation will be employed to provide additional confidence in the data gathering and storage process (all).

The NDA has been working in collaboration with the British Geological Survey to develop a high-level data management strategy. It will be essential that the systems are in place, tested and are fully operational before acquisition of investigation data commences. Such a system would ensure that the data are:

- Coherent and consistent through the application of scientific standards;
- Captured and processed using industry standard data capture systems;

- Provided with a clear audit trail to data sources;
- Managed in an environment that permits full version control and maintenance of archives;
- Accessible as and when required;
- Maintained in a secure and controlled environment.

12.4.10 Documentation

In SAFIR-2, SCK/CEN-ONDRAF/NIRAS used two types of forms in order to the traceability of the data collection process. The first form is the "data collection form**"**, which gives a one-page overview of the selected values for the input parameters (both best estimate value and pdf), the main references and the names of the experts (at least one) from the assessment basis group and of the safety assessor involved with the data collection. The second form is called the "annex" which can give much more detailed information on the data that were available, a (short) discussion on their relevance, the reasoning applied to derive a best estimate value, and the distribution and its parameters. The data collection forms as well as the annexes have been collected in a report [Marivoet 99].

In recent Safety Assessment a significant effort has been spent in the documentation of the models and data used. In Finland Posiva foresees the publication of the collection of Models and Data used in the Safety Case as a report in its own right. The *Models and Data Report* will act as an interface between the safety case activities and the principal supporting activities. The information included in the *Models and Data Report* is selected on the basis of its safety relevance: the EBS and site data that directly provide the input to the safety case are discussed in these reports, while more details can be found in the supporting background reports, such as the Site Descriptive Model report and various technical descriptions of the engineered barrier system. The quality of the Site Descriptive Model report is mainly ensured by the application of scientific principles, while the methods of quality control for the technical barrier design and implementation depend on the nature of the materials and technology in question. The *Models and Data Report* captures the most significant information related to safety, the quality of which is of primary importance for confidence in long-term safety.

The most recent Safety Cases include separate documents to present the models and the data used in the assessments. In Sweden SKB described the models and data used in SR-CAN project in two separate documents, one dealing with data [SKB, 2006a] and other with models [SKB, 2006b]. In Switzerland NAGRA summarised the data and the models used in Project Opalinus Clay in a single report [NAGRA, 2002]. A similar approach was followed by Andra in Dossier 2005 and SCK/CEN-ONDRAF/NIRAS in SAFIR 2 [Marivoet, 1999].

In France (Andra), the input data and the fruits of the analyses conducted under the Dossier 2005 are structured into a documentary architecture organised according to the safety approach. The peculiarity of the Dossier 2005 is that it is based on the observations and the results from experiments carried out on a real site, namely, on the Meuse / Haute-Marne laboratory site. Input data is structured in five different documents, with the following contents:

- The input data on the packages are described in the design inventory document which presents the main characteristics of the packages.
- The state of knowledge on the Meuse / Haute-Marne laboratory site is presented in the site reference document which includes detailed results on experimental work.
- The knowledge regarding the behaviour of the different materials in the repository and the transport of radionuclides and chemical toxics is presented in three reference documents: one for the “materials” in the repository, one for the “behaviour of the packages” and one dealing with the “behaviour of the radionuclides and the chemical toxics”.

12.5 Application and experience

Implementers have been developing and using models, and selecting the necessary data, for the safety assessment of geological repositories for many years. Regulators are familiar with the safety assessment methodologies also, and in some cases (IRSN) have developed their own models.

To process such amount of data and models, implementers have developed simulation platforms that enable to manage very large amount of data and execute complex calculation. The ALLIANCE platform developed by Andra and CEA is an example.

A brief summary of the experience of the different countries in safety assessments of geological repositories is described in section 11.5.

12.6 Developments

The developments foreseen by the different organisations are strongly affected by the stage of the national waste disposal programme. Ongoing and future developments are presented in this section.

Implementers

All the implementers that are preparing a new iteration of the Safety Case are developing more advanced models and improving data quality. An example could be the current and future activities programmed by NDA related to data needs for site description and safety case models that are orientated to:

- Update the national radioactive waste inventory to reflect the evolutions or changes in waste management strategies, decommissioning programmes, commercial, technological or regulatory reasons, and current information;
- Complete the study to develop a strategy for the development of a data management system to store and manage the information arising from a site characterisation programme;

- Continue with the studies to develop an improved definition of discipline-based information requirements for a site characterisation project with peer review by a group of specialists;
- Continue to identify gaps in information in the models that would need to be addressed by site investigations;
- Further develop the procedures for addressing uncertainty in data;
- Develop a strategy for communication of information on the site geosphere characterisation to all interested stakeholders. This entails: organisation of data and information in a form that it is readily available to potential audiences ranging from a lay audience to technical specialists; the use of appropriate reports, brochures, and web sites together with a 'helpline' for requests for information;
- Maintain the research and development programme on waste form research, gas generation, near-field research, geosphere research, biosphere research and criticality safety research.

For the next Safety Case SCK/CEN-ONDRAF/NIRAS intend to express parameter values as a range rather than as a best-estimate. Experts will be requested to provide two ranges of values for a specific parameter, the so-called "source range" and "expert range".

- The source range of a parameter takes account of the uncertainties due to the simplifications inherent to the conceptual modelling but also of those stemming from hypotheses of the conceptual model which are less well supported and remain to be confirmed. This range rests on little expert judgment since all possible values of the parameter induced by the poorly-supported hypotheses of the conceptual model are covered.
- The expert range is meant to be a more realistic range of parameter values than the source range and is arrived at by making expert assumptions regarding the poorly-supported hypotheses. Therefore the expert range implies much more expert judgment than the source range. The expert range is a subset of the source range: it is equivalent to the source range less the impact of the uncertainties on parameter value. Whereas the source range is defined by a minimum and maximum value representative of the conservative and optimistic case, the best estimate of the expert range represent the value expected by the expert for a particular parameter.

Using the two-range approach, the safety assessor will select the minima, maxima or best estimates to represent a conservative or realistic calculation case.

In addition, SCK/CEN-ONDRAF/NIRAS intends to discuss the uncertainties in parameter data according to three categories of uncertainties (arising from the specificities of the Belgian RD&D programme):

- Upscaling - the degree to which observations and measurements made over relatively short intervals of space and time may be assumed to apply over the larger spatial and temporal scales of interest in safety assessment.

- Transferability - the degree to which observations and measurements made at one location in the host formation (e.g. in the Mol-Dessel area) may be assumed to apply at another location (the actual repository site, which may be elsewhere in the potential siting area).
- Evolving conditions - the impact of phenomena, such as climate change and geological events, that may affect the disposal system occurring over time in a given scenario and assessment case.

Finally, SCK/CEN-ONDRAF/NIRAS is currently implementing a database system equipped with a versioning and reviewing system in order to guarantee the traceability of the selection of the parameter ranges from evaluations, based on experimental, process modelling or literature studies, performed by the assessment basis group up to their use in the safety calculations.

In France, Andra is working in order to present a Demand of Authorization of Creation of the storage at the end of 2014. Andra will optimize the concept and will complete the knowledge to answer to the regulators, reduce the margins of uncertainties and so increase the degree of confidence in the safety in operational and after closure phases. In practice, the studies will aim at:

- completing the knowledge on waste packages, the site and the phenomenology of the evolution of the disposal system to reduce the residual uncertainties,
- prolonging the acquisition of experimental data in the underground laboratory,
- performing new technological essays at real scale,
- performing detailed geological survey and Callovo-Oxfordian characterisation on a restricted zone with the aim of setting-up the future surface and underground facilities, toward license application,
- understanding more finely the phenomena governing the evolution of the storage and their coupling,
- reducing the residual risks during the operational phase without degrading the long-term performance of the repository.

Such refinements imply the development of simulations tools, databases and their management.

Within PAMINA Task 2.2.A, a systematic procedure to generate probability distributions for uncertain parameters has been developed [Becker, 2008]. The guidelines presented in that document are in agreement and support the methodologies already used by some implementers and that are described in section 12.4.7.

In PAMINA Task 2.2.A an expert elicitation exercise has been undertaken by Enresa, JRC and Amphos21. In this exercise a generic protocol for the expert elicitation has been developed by JRC, and has been applied to the definition of probability distributions for the solubility limits of five relevant chemical elements in the near field of a repository in granite [Bolado, 2009].

Regulators

Some countries (Finland, France and United Kingdom) already have detailed regulations that provide broad guidance and requirements on how the implementer should generate the data to be used in a Safety Case. Other countries (such as Belgium and Germany) are in the process of developing their own detailed regulations that will include guidance and requirements on modelling and data selection (both topics are closely related). There is a general trend of moving from generic regulations (focused on a dose/risk limit for the disposal facility) to more detailed regulations that establish requirements and provide guidance on the different aspects of repository development, when a national disposal programme moves from the phase of conceptual studies to more advanced phases of site selection and detailed design of the facilities.

Implementers are responsible for carrying out all the necessary investigations of the site or sites and of materials and for assessing their suitability, and for providing data for safety assessments. Regulations provide guidance and requirements applicable to the data generation and selection processes, and will remain at that degree of detail. Regulations set state-of-the-art standards for input and data selection to demonstrate safety, but leave the details of how to provide evidence to the implementer (and their appraisal up to the regulatory body).

Open discussion between implementers and regulators is very useful from the initial stages of the development of a repository. For the implementers it is particularly useful to have guidance on regulators expectations.

The following topics related to data selection are expected to draw particular attention of the regulators in the future:

- Quality assurance procedures implemented for developing the models and generating the data to be used in the Safety Assessment. Proper documentation and traceability of the process of data generation.
- Inclusion of uncertainties in the data generation process.

12.7 Conclusions

During the workshop fruitful discussions on modelling strategies were held. The conclusions of these discussions are summarised in this section.

Site characterisation

At early stages of the development of a repository, Safety Assessments can be done using generic geosphere data. The results obtained can provide useful guidance for site characterisation, identifying the properties of the geosphere that have greater effect on repository behaviour.

At later stages site characterisation is a long and complex process that will generate a great amount of data during a long time period. Several complementary strategies are used to generate data, including boreholes and experiments in an underground research laboratory. Handling these data requires a particular strategy. Before the start of site characterisation a QA programme must be available, covering all the organisations involved.

Site characterisation can be organised through the development and progressive updating of a series of interrelated Site Descriptive Models (Geology, Hydrogeology, Geotechnical, Transport properties, Thermal properties and Biosphere, for instance). The geology model is the framework on which all the other models are built, and the data generated during the site characterisation will be organised around these models.

Initially Site Descriptive Models may change significantly when new site information is available, but at later stages models will become stable as further information is included. This stability of the models can be used as a potential criterion for deciding completion or continuation of the investigations.

Waste characterisation

For the organisations that foresee many different wastes to be disposed of in the repository, waste characterisation (determination of radionuclide inventory and waste properties) is a complex topic that requires a significant effort. For those organisations, the radionuclide inventory to be disposed is considered as basic input data to be used for repository design.

For the participants that consider only spent fuel or HLW in their assessments, waste characterisation is simpler.

The role of sensitivity analysis

Sensitivity analyses from previous Safety Assessments are useful to identify the parameters that control repository behaviour. This allows paying special attention to the most relevant parameters during the data selection process, and focusing R&D efforts in reducing the uncertainty on these parameters.

Posiva intends to include in the document presenting the data used in the Safety Case information about the relevance of each parameter, on the basis of the results of the sensitivity analyses.

Definition of parameter values for deterministic calculations

Most organisations consider that probabilistic and deterministic calculations are complementary and include both types of calculations in the Safety Case. As a consequence, there is a need to generate values and probability distributions for the different parameters included in the calculation models.

For deterministic calculations two different classes of parameter values are usually selected: “best estimate” and “conservative”. In general, the use of “best estimate” parameter values in the deterministic calculations is favoured, although in some cases “conservative” values are preferred for the consequence analysis.

Some organisations consider useful to generate both “best estimate” and “conservative” values of the parameters to be used in different sets of calculations. This would reduce the tendency of the experts to be conservative when selecting “best estimate” values (a problem identified by SCK/CEN/ONDRAF·NIRAS). The comparison of the results of the two sets of calculations (best estimate and conservative) provides an indication of the margin of improvement of the calculated performance of the repository if the uncertainties leading to the conservative values are reduced.

Definition of probability distribution functions for stochastic calculations

The uncertainties in the parameters must be identified explicitly during the process of data selection. These uncertainties will be the basis to define the probability distribution functions to be used in the stochastic calculations.

The criteria followed by the different organisations to produce the probability distributions are quite similar.

- First a reasonable range of values is identified.
- If there is more than a factor 5 or 10 of difference between the high and the low values in the range, a logarithmic distribution is used. Otherwise, a linear distribution is adopted.
- If it is considered convenient to give more statistical weight to a particular region of values (around the “best estimate“, for instance) a triangular distribution with the most probable value in that region is used. Otherwise, a uniform distribution is adopted.

Expert elicitation

During the development of a Safety Case in general, and in the selection of data values for the assessment in particular, a great amount of expert judgement is involved. Safety assessment experts and the specialists must take many decisions during the selection of parameter values.

Most implementers do not use formal expert elicitation to generate the data used in the Safety Case. Only NDA uses this technique to generate the probability distributions for all the uncertain parameters, and Posiva uses expert elicitation only for very uncertain parameters.

Quality Assurance

All the participants agree on the importance of a comprehensive QA programme that must cover, among other topics, the generation of data within the project (experiments, site characterisation,…) and the selection of data to be used in the Safety Case. The objective must be to ensure the high quality of the data generated and fulfil the following key requirements:

- Justification and traceability of the whole process of data generation and selection.
- Review by independent experts of the process followed and the values obtained.
- Proper documentation of the process.
- Data consistency.

Many documents will be produced in the process of data generation. One of the “top level” documents of the Safety Case should be a document summarising the parameter values selected for the different models, and the basis for their selection. This document should provide enough information to allow understanding the basis for the data selection done, and contain references to reports where more detailed information is available.

In some countries two different documents are generated, one describing the models developed and other describing the data selected. Since models and data are closely related, other countries prefer to present models and data in the same document.

12.8 References

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13. Uncertainty management and uncertainty analysis

13.1 Introduction

Uncertainty is inherent to all kind of safety assessments. In general, uncertainties arise from imperfect knowledge of the system to be assessed and its evolution. In the case of geological disposal, there are specific characteristics which enhance the relevance of uncertainties for the post-closure safety assessment.

In the European Pilot Project [Vigfusson, 2007] it is stated that "uncertainties concerning the safety of repositories are unavoidable due to the complexity of the phenomena of concern and the scales in time and space under consideration, and their management is central when developing a repository system and assessing its safety".

In the first place, the time scales to be considered in the safety assessments of geological repositories are very long. Typically, the assessment is extended to hundreds of thousands of years or more. These long time scales introduce further sources of uncertainty, make some uncertainties larger and exclude the assumption that after some time (a few hundred years) human actions may be accounted for preventing, detecting, mitigating or otherwise reacting to the deviation from the expected evolution of the repository. The long time scales have also as a consequence that the design and the long term safety assessment cannot build on the experience of previous facilities of the same kind.

Another important characteristic of geological repositories in regard of safety assessment uncertainty is the variability of the natural media in which the repository is placed. Natural media are essential components of the repository system, for two reasons. Firstly the natural barrier plays a role in the confinement of the contaminants disposed of and also in the protection of the inner components of the repository system (i.e. the engineered barriers). Secondly the natural environment controls the background conditions in which processes influencing the performance of the different safety barriers take place. Variability of the natural media occurs both in time and in space. Initial variability of the natural media ("the site") is the object of site characterisation and site monitoring; nevertheless the space scales of the site put practical limits to exhaustiveness and the level of resolution at which the relevant features of the site can be known. The characteristics of a site are not constant: on the contrary, they will evolve under the influence of factors both external and internal to the repository system, including the interactions with the man made components and with the waste. Furthermore, as it has been pointed out above for the time scales, the space scales make impossible the direct test of the repository system in order to verify its performance.

For the reasons explained above, the means to assess the long term safety are necessarily indirect. Tests and experiments are only possible over short duration and in contexts which can only approach those expected in reality. Experimental data need to be extrapolated to the required scales; this is done typically using models, based on the understanding of the basic processes that control or bound the evolution of the physical entities in the future. This extrapolation at very different scales is another source of uncertainty.

The end point of the quantitative safety assessment of a geological repository is the mathematical calculation of a safety indicator, and its comparison with a relevant numerical criterion, as defined by the regulations. Nevertheless, this comparison is meaningless if there is not an analysis of how the different uncertainties affect confidence in the safety indicator. The aim of uncertainty analysis is to provide confidence in the bases and arguments developed to support the claim that the repository is safe, and that the mathematical estimation of the safety indicators does not misrepresent the expected performance of the repository.

In most regulations and guidance documents developed for geological repositories, it is emphasised that uncertainty analysis is a key component of the safety assessment. An essential activity within the safety assessment is the identification of uncertainties that have the potential to undermine safety. Thus, safety assessment needs to be integrated within the management strategy. In the safety case, the connection needs to be made between key uncertainties that have been identified and the specific measures or actions that will be taken to address them [NEA, 2004a]. The importance of this aspect is recognized by the agencies involved in the development of geological disposal programs. In the safety assessments made so far, it can be observed a clear trend towards a more extensive and structured consideration of the uncertainty issue, which involves two aspects:

- The control of the uncertainties in the overall development programme, through strategic provisions, at both the technical and organizational levels, in order to reduce and improve the basis for identifying, controlling and analysing the uncertainties; and
- The actual identification and handling of the uncertainties in the safety assessment.

These two aspects are related to the double title of this report: Uncertainty Management and Uncertainty Analysis respectively.

The issue of uncertainties has received a lot of attention on the part of both the Regulators and Developers, and has been a focus of international activities [NEA, 2004a] [NEA, 2006].

13.2 Regulations and guidelines

Most of the national regulations and international guidance emphasize the importance of uncertainty analysis in the safety assessment.

In [IAEA, 2006] a requirement of geological disposal is that there must be sufficient confidence in the results of the safety assessment. This will be facilitated by identifying the features and processes that provide safety and also the features, events and processes that might be detrimental to safety, showing that they are sufficiently well characterized and understood. Where there is uncertainty, it will be taken into consideration in the estimation of safety.

The understanding of the performance of the disposal system and its safety related features and processes will evolve as more data are accumulated and scientific knowledge develops. Early in the development of the concept, the data and understanding need to be sufficient to provide the level of confidence necessary to commit the resources to further investigation. Before the start of construction, during emplacement and at closure, the understanding must be sufficient to support the safety case in satisfying the applicable regulatory requirements. In establishing these requirements, it is important to recognize the multiple components of uncertainty that are inherent in modelling complex environmental systems and that there will inevitably be substantial uncertainties associated with projecting the disposal system performance. Furthermore, it is required that the post-closure safety case and supporting assessment identify and present an analysis of the associated uncertainties.

[SKI, 2001] requires that the following shall be reported (in the safety assessment): "how uncertainties in the description of the functions, scenarios, calculation models and calculation parameters used in the description as well as variations in barrier properties have been handled in the safety assessment, including the reporting of a sensitivity analysis which shows how the uncertainties affect the description of barrier performance and the analysis of consequences to human health and the environment".

Furthermore in the general recommendation on the former regulation is stated that *"these uncertainties can be classified as follows:*

- *Scenario uncertainty: uncertainty with respect to external and internal conditions in terms of type, degree and time sequence,*
- *System uncertainty: uncertainty as to the completeness of the description of the system of features, events and processes used in the analysis of both individual barrier performance and the performance of repository as a whole,*
- *Model uncertainty: uncertainty in the calculation models used in the analysis,*
- *Parameter uncertainty: uncertainty in the parameter values (input data) used in the calculations,*
- *Spatial variation in the parameters used to describe the barrier performance of the rock (primarily with respect to hydraulic, mechanical and chemical conditions).*

There are often no clear boundaries between the different types of uncertainties. The most important requirement is that the uncertainties should be described and handled in a consistent and structured manner.

The evaluation of uncertainties is an important part of the safety assessment. This means that uncertainties should be discussed and examined in depth when selecting calculation cases, calculation models and parameters values as well as when evaluating calculation results.

The assumptions and calculation models used should be carefully selected with respect to the principle that the application and the selection should be justified through a discussion of alternatives and with reference to scientific data. In cases where there is doubt as to a suitable model, several models should be used to illustrate the impact of the uncertainty involved in the choice of model.

Both deterministic and probabilistic methods should be used so that they complement each other and, consequently, provide as comprehensive a picture of the risks as possible.

The probabilities that the scenarios and calculation cases will actually occur should be estimated as far as possible in order to calculate risk. Such estimates cannot be exact. Consequently, the estimates should be substantiated through the use of several methods, for example, assessments by several independent experts. This can be done, for example, through estimates of when different events can be expected to have occurred.

Based on scenarios that can be shown to be especially important from the standpoint of risk, a number of design basis cases should be identified.

Together with other information, such as on manufacturing method and controllability, these cases should be used to substantiate the design basis such as requirements on barrier properties.

Particularly in the case of disposal of nuclear material, for example spent nuclear fuel, it should be shown that criticality cannot occur in the initial configuration of the nuclear material. With respect to the redistribution of the nuclear material through physical and chemical processes, which can lead to criticality, it should be shown that such a redistribution is very improbable.

The result of calculations in the safety assessment should contain such information and should be presented in such a way that an overall judgement of safety compliance with the requirements can be made".

[SSI, 1998] endorse the above referenced SKI's regulations, and specifies that "the different categories of uncertainties, which are specified there, should be evaluated and reported on in a systematic way and evaluated on the basis of their importance for the result of the risk analysis. The report should also include a motivation of the methods selected for handling different types of uncertainties, for instance, in connection with the selection of scenarios, models and data. All calculation steps with appurtenant uncertainties should be reported on.

Peer review and expert panel elicitation can, in the cases where the basic data is insufficient, be used to strengthen the credibility of assessments of uncertainties in matters of great importance for the assessment of the protective capability of the repository".

In France, [JORF, 1991] requests that uncertainty ranges be provided for the radiological consequences of the repository. In addition, sensitivity analysis should be carried out in order to identify priority areas for further effort, and to help in the assessment of the uncertainties affecting the results of the safety assessment. A very similar statement regarding the information to be provided in the safety assessment on the uncertainties is found in the Swiss HSK-R-21/f [HSK & KSA, 1993].

In Finland, the Government Decision on the safety of disposal of spent nuclear fuel (478/1999) requires that "*the data and models introduced in the safety analysis shall be based on the best available experimental data and expert judgement. The data and models shall be selected on the basis of conditions that may exist at the disposal site during the* *assessment period and, taking account of the available investigation methods, they shall be site-specific and mutually consistent. The computational methods shall be selected on the basis that the results of safety analysis, with high degree of certainty, overestimate the radiation exposure or radioactive release likely to occur. The uncertainties involved with safety analysis and their importance to safety shall be assessed separately". On this issue, the Radiation and Nuclear Safety Authority [STUK, 2001] specifies that the safety analysis shall include "uncertainty and sensitivity analyses and complementary discussions on the significance of such (unlikely disruptive events) impairing long-term safety phenomena and events which cannot be assessed quantitatively". And further on:" the computational methods shall be selected on the basis that the results of the safety analysis, with high degree of certainty, overestimate the radiation exposure or radioactive release likely to occur*".

In a similar way, the so-called "Franco-Belge" document [FANC, 2004] states that the consideration of uncertainties is a central element of a safety case. It can be undertaken, among other ways, by the use of conventional deterministic or probabilistic uncertainty evaluation tools.

In the UK [EA, 1997] the regulators have set out guidance on the principles and requirements against which any application for authorisation of a radioactive waste repository will be assessed. It asks that the information provided by the developer includes, among other things: *"…overall results from probabilistic risk assessments of the disposal system which explore the relevant uncertainties; suitable breakdowns of such risk assessments to show, for example, the probability distribution of doses and the contribution of important radionuclides; [and] a comprehensive record of the judgements and assumptions on which the risk assessments are based…"*. The expectation value of risk has to be compared with the regulatory risk target. The expectation value of risk is obtained by averaging the calculated risk from each probabilistic realisation.

In the US, detailed and comprehensive regulations have been implemented for the licensing of the WIPP disposal facility. These regulations provide the developer with a detailed, prescriptive path for the conduction of supporting assessments, and include the assessment period to be covered (10,000 years), limits on the cumulative release of radionuclides to the accessible environment, assumptions to be used in assessing particular Features, Events and Processes (FEPs), and requirements on the treatment of uncertainties. In addition to complying with radionuclide release limits, WIPP must comply with individual and groundwater protection standards [Galson, 2007] .

Also in the U.S., the EPA and the NRC are currently developing the standards that will apply to the disposal of HLW and spent fuel in the potential repository at Yucca Mountain (proposed 40 CFR Part 197 and 10 CFR Part 63). The requirements of the proposed rule in the matter of uncertainties are described by the DOE-YMP in its contribution to PAMINA Work Package 1.2 as follows [Galson, 2007]:

"In the Supplementary Information published with the rule, the NRC has stipulated the application of a probabilistic framework for total system performance assessment (TSPA):

‘Demonstration of compliance with the postclosure performance objective specified at § 63.113(b) requires a performance assessment that quantitatively estimates the expected annual dose, over the compliance period and weighted by probability of occurrence, to the average member of the critical group. Performance assessment is a systematic analysis of what can happen at the repository after permanent closure, how likely it is to happen, and what can result, in terms of dose to the average member of the critical group. Taking into account, as appropriate, the uncertainties associated with data, methods, and assumptions used to quantify repository performance, the performance assessment is expected to provide a quantitative evaluation of the overall system’s ability to achieve the performance objective. (64 FR 8640)’

Note that the NRC not only anticipates that there will be significant uncertainties (proposed 10 CFR 63.101), but the NRC also requires the TSPA take into account uncertainties in characterizing and modeling the barriers (proposed 10 CFR 63.114). Furthermore, proposed 10 CFR 63.113(b) (64 FR 8640) requires a demonstration of compliance by calculating an expected annual dose, defined as follows:

‘The expected annual dose is the expected value of the annual dose considering the probability of the occurrence of the events and the uncertainty, or variability, in parameter values used to describe the behavior of the geologic repository (the expected annual dose is calculated by accumulating the dose estimates for each year, where the dose estimates are weighted by the probability of the events and the parameters leading to the dose estimate). (64 FR 8640)’ ”

In Canada, [CNSC, 2006] includes the following guidance on the treatment of uncertainty: “The strategy used to demonstrate long term safety may include a number of approaches, including, without being limited to:

- Scoping assessments to illustrate the factors that are important to long term safety;
- Bounding assessments to show the limits of potential impact;
- Calculations that give a realistic best estimate of the performance of the waste management system, or conservative calculations that intentionally over-estimate potential impact; and
- Deterministic or probabilistic calculations, appropriate for the purpose of the assessment, to reflect data uncertainty.

Probabilistic models can explicitly account for uncertainty arising from variability in the data used in assessment predictions. Such models may also be structured to take account of different scenarios (as long as they are not mutually exclusive) or uncertainty within scenarios”

In the Netherlands a safety report has to show that risks and individual doses are below the regulatory limits. However, a license application will also include an EIS (Environmental Impact Statement), which follows more or less the ICRP principles for Radiation Protection, i.e.: (1) justification, (2) optimisation, and (3) compliance with limits. The EIS uses the safety report to show compliance. For optimisation the EIS needs more indicators to be able to compare with alternative options. Presently the only indicators are dose and risk, for which there are reference values and constraints.

The Czech State Office for Nuclear Safety (SUJB) issued in 2004 a methodological guide for compilation of a safety report in support of siting application for a radioactive waste repository. This guide addresses the evaluation of uncertainties stemming from insufficient knowledge and complexity of the natural environment.

With the notable exception of the U.S., where detailed requirements are set, the regulatory approach to treatment of uncertainties that many countries are taking is not prescriptive, and is defined through the publication of non-binding guidances or “expectations” with respect to scope and methods for performing the assessments, coupled with licensing procedures at local and national levels. For example, this approach has been discussed in the European Pilot Project [Vigfusson, 2007] and is also the way followed in Canada [Galson, 2007].

13.3 Terminology

13.3.1 Formally defined terms

There are not official or generally accepted definitions for some of the terms used in documents dealing with uncertainty analysis in the field of geological disposal. For these, working definitions or explanations commonly used are discussed in section 13.3.2 below. Other terms are defined either in national regulations or in international references.

In [IAEA, 2007] **uncertainty analysis** is defined as an analysis to estimate the uncertainties and error bounds of the quantities involved in, and the results from, the solution of a problem. More specifically in the field of geological disposal uncertainty analysis is a component of the safety assessment that analyses how the uncertainties which affect the different elements (data, assumptions, etc.) of the assessment propagate along it and affects the uncertainty of (or conversely the confidence in) the results (the safety indicators).

Sensitivity analysis is defined by IAEA as a quantitative examination of how the behaviour of a system varies with changes, usually in the values of the governing parameters. A more specific common meaning of this term is analysis to investigate the dependencies of the result of the assessment on the alternative input elements (data, assumptions…) and in particular the dependencies of the uncertainties of the results on the uncertainties of the input elements to the assessment.

The definition given for **risk** in the same reference is: The probability of a specified health effect occurring in a person or group as a result of exposure to radiation. In [SSI, 1998] the health effects considered are cancer (fatal and non-fatal) as well as hereditary effects in humans, *“in accordance with paragraphs 47-51 in Publication 60, 1990, of the International Commission on Radiological Protection”*. In quantitative risk assessment the risk associated with an exposure is the product: consequence of the exposure times the probability of occurrence, and the total risk is the sum of this product extended to all the exposures (sum of probabilities equals one). The consequence of the exposure is calculated multiplying the dose by a conversion factor.

A close concept to risk, as it combines dose and probability in an aggregated indicator is **expected dose**, which is the dose times the probability of its occurrence; this indicator is used in the Finnish regulations for the long term safety of geological disposal to set constraints for unlikely events (deep well, rock movement, glacial climate) [STUK, 2001]. In the U.S. Yucca Mountain Project, the regulations establish safety criteria in probability weighted doses over the full spectrum of expected future situations, which is the total expected dose. For a single unlikely event, this concept coincides with the Finnish guidance that has been referred to. In both cases, there is a constant ratio to risk (the conversion factor).

13.3.2 Working terms

As explained in the previous section, some of the terms used in the field of uncertainty are not universal, or official definitions that are generally accepted are not available. Users usually define them in their documents as required. Relevant terms used within the WP1.1 of Pamina Project or by the organisations which have made developments of interest for this task report are introduced below.

Risk dilution is an issue which has been discussed for long time. In [NEA, 1997] it is said that "*this term is used to describe a situation in which an increase in the uncertainty of the input parameters of a model (while holding the mean of the distributions constant) leads to a decrease in the mean of an output quantity (…). If overestimation of uncertainty results in mean consequences being reduced, the unfortunate effect is that what appears to be a conservative step (overestimating the degree of uncertainty) leads to an overoptimistic assessment of mean system performance". In [NEA, 2004b] risk dilution is "an issue for both risk based and non-risk based approaches. The concept of an annual risk criterion (which can be expressed as taking 'the peak of the means') can lead to an apparent lowering of risk - risk dilution. One concern appears to be averaging the consequences of events with short duration but with uncertainty as to their time of occurrence. Using the 'mean of the peaks' (also termed "total risk") is one way to get around this problem (although currently no regulations provide guidance on this issue). The use of the mean of the peaks is comparable to the use of a dose criterion, which gives the same level of protection for all individuals irrespectively when they are exposed. This is also compatible with the concept of sustainable development in that allows the exploitation of natural resources at any time. The mean of the peaks approach can, however, lead to misleading results by effectively combining results from events that are in fact independent. Some countries have therefore decided not to take this approach".*

The very title of this chapter refers to uncertainty management and uncertainty treatment, which are worthy of a definition. In [NEA, 2004b] the analogue concept of *"risk management was interpreted as the whole sequence of risk assessment, decision making and consecutive actions that affect the realisation of the risk"*.

The common understanding between the organisations contributing to this handbook is that the focus of uncertainty management is the strategy followed in the overall repository programme to control the uncertainties which may influence the performance of the long term safety functions of the repository system; it includes the full range of actions and measures taken in the stepwise repository programme. Uncertainty analysis is a sub-set of the former, and refers to the way uncertainties are handled in the safety assessment. This is clearly expressed by SCK/CEN and ONDRAF/NIRAS: *"uncertainty analysis is the analysis by different methods and tools that aims to quantify the uncertainty in the considered output variable (e.g. calculated doses or radionuclide fluxes)"…whereas "uncertainty management is the broader activity of deciding on the level of the disposal programme how to deal with the uncertainties, i.e. what measures have to be or will be taken in the disposal programme to systematically identify the uncertainties and decide for each of the identified uncertainties the way to treat them (e.g. reduction of uncertainties through additional design modifications or site and waste characterisation actions, conservative assumptions in assessments)"*.

Several terms appear in the classification of uncertainties made in different programmes. Uncertainties are often classified as **epistemic** which are knowledge-based and, therefore, reducible, and **stochastic** uncertainties, which are random and irreducible. It has been claimed that there are very few purely stochastic uncertainties. This classification is not often very useful, as most uncertainties are a mixture of both types. The epistemic character, however, is dominant in most cases (GRS-B).

From a methodological point of view the classification of uncertainties is of special interest [Galson, 2007]:

- Uncertainties arising from an incomplete knowledge or lack of understanding of the behaviour of engineered systems, physical processes, site characteristics and their representation using simplified models and computer codes (for example, the incorrect establishment of initial conditions/boundary conditions, of the dimensionality or the level of resolution (discretisation) (SCK/CEN and ONDRAF/NIRAS). This type of uncertainty is often called **"model"** uncertainty.
- Uncertainties associated with the values of the parameter that are used in the implemented models. They are termed **"parameter"** or **"data"** uncertainties (e.g., for SKB "data uncertainty concerns all quantitative input data used in the assessment" [NEA, 2007])
- Uncertainties associated with significant changes that may occur within the engineered systems, physical processes and site over time. These are often referred to as **"scenario"** or **"system"** uncertainties. [Galson, 2007]

The former classification is used by many organisations. But others apply somewhat different terms and/or nuances in the definitions. Enresa and Posiva use the term **"conceptual"** uncertainty which is related to the term model uncertainty referred to above. It is the same for SKB, for which *"conceptual uncertainty essentially relates to the understanding of the nature of processes involved in repository evolution. This concerns not only the mechanistic understanding of a process or set of coupled processes, but also how well they are represented in a possibly considerably simplified mathematical model of repository evolution"* [NEA, 2007].

Posiva uses the term **"numerical"** uncertainty instead of "data" or "parameter" uncertainty used by most organisations.

Some organisations prefer alternative terms to scenario uncertainty. Enresa uses the term **"system evolution"** uncertainty which is similar, but emphasises the fact that given a scenario, which is affected by uncertainty in its characteristics, there are uncertainties in the way it influences the characteristics of the system. This view approaches SKB's term **"system"** uncertainty [NEA, 2007] which *"concerns comprehensiveness issues, i.e. the question of whether all aspects important for the safety evaluation have been identified and whether the analysis is capturing the identified aspects in a qualitatively correct way, e.g. through the selection of an appropriate set of scenarios. In short, have all factors, FEPs, been identified and included in a satisfactory manner?"* [NEA, 2007]. In the same context, NRG uses the term **"future developments"**.

Some organisations devise more distinct uncertainty classification schemes:

Andra distinguishes the following classes of uncertainties:

- Independent of the repository behavior (e.g.: waste inventory)
- Intrinsic characteristics of the repository components (this class may be related to parameter uncertainty)
- Affecting processes controlling repository evolution:
  - Affecting the prediction of long term behavior
  - Based on short term observations
  - Limited validity of models (this class may be related to conceptual uncertainty)
- Technological uncertainty: a) alternative operating methods (e.g. excavation method), b) limited knowledge on the application of technologies in the underground
- External events: a) natural (tectonic, climate), b) human actions (anthropogenic effects, human Intrusion).
- Design provisions

NRI and RAWRA use the following classification:

- Time uncertainty – we do not know the behaviour of barriers over thousands of years.
- Structural uncertainty – we do not know the effect of some factors (temperature, radiation, microbial) on the behaviour of barriers.
- Metric uncertainty – we do not know whether the physical of chemical data have been well determined.
- Translation uncertainty – we cannot explain causes of some effects.

A **"what if scenario"** is generally understood to be a scenario that is not physically impossible, but outside the range of expected possibilities supported by scientific evidence [NEA, 2006]. Such scenarios are not expected, so they are not factored in the measure of performance of the repository system, but they are frequently used as a method of analysis to improve the understanding of the system and its evaluation. They can also be used as part of sensitivity analyses, particularly in deterministic studies. In the Belgian programme the term “what if cases" is preferred to imply that they are representative of calculation cases rather than resulting from a series of physically possible events (determining the scenarios).

Enresa uses the term **“variant”** to refer to “what if” scenarios characterised by specific deviations from the scenarios considered in the evaluation, usually by defining a single modification of an assumption or model in the original scenario (Enresa). In the Belgian programme, the term **“variants”** are used in a different way: they *“are considered within a specific scenario such as the distinction made between different possible evolutions of climate (undisturbed natural evolution or greenhouse effect) in the expected evolution scenario”*.

Upscaling is often cited as one of the causes of uncertainty in the safety assessment. Upscaling relates to either spatial or time extrapolation. It occurs in particular for:

- Transfer of data from a context to another (e.g. data from an experiment to the repository system)
- Attribution of data obtained at a point in space to a larger domain (e.g. site feature measured at a point extended to a model cell in a mesh)
- Extrapolation of short term observation to long timescales

13.4 Methodology

13.4.1 Uncertainty management

The overall strategy for uncertainty management can be synthesised by four words: i**dentify, avoid, reduce** and **assess**. The safety strategies of the repository development programs in the different countries have numerous features that are relevant for uncertainty management, even if they are not explicitly intended for, or not exclusively for that purpose. Below there is a compilation of the relevant uncertainty management features that can be identified in the national repository development programmes, with comments on how they contribute to uncertainty management. The various repository development programs which explicitly refer to each feature as part of their uncertainty management scheme are mentioned; in many others such features are also accounted for implicitly:

- *Stepwise development process* of the repository programme: at each step the uncertainties are identified, analysed and ranked: priorities are defined to systematically reduce and/or address remaining uncertainties in the next step of the programme (Enresa, Posiva, IRSN, NDA). In the case of Andra, safety is the driving objective of the programme from the initial stage.
- *Regulatory framework*, independence of the Regulatory Authority, openness and participation of multiple stakeholders in the development process, which introduce cross-scrutiny (Enresa, NDA)

- *Long timescales of the project*, from the initial planning phase to the closure of the repository, which provides opportunity for i) multiple opportunities for re-assessment of the acceptability of the repository ii) the involvement of different individuals (Enresa)
- *Robust repository concept* (i.e. low sensitivity to uncertainties), for example by the use of sound principles, as the multi-barrier and multi-function system, passive safety (Andra, SKB, NRG, Nagra, Enresa, SCK/CEN, ONDRAF/NIRAS).
- *Flexibility* of the repository development programme: i) to accommodate changes in the amounts and quantities of waste, ii) to deal with new site data, iii) to take decisions (in particular on technological issues) when sufficient knowledge is available, keeping alternative options available until a decision is needed. Flexibility provides room for inclusion of results from technical developments, new R&D results, and more detailed site understanding (SKB)
- *Intrinsically sound repository components* (e.g. use of reliable materials and technologies for EBS (Andra, SKB, NDA), excellence of site characteristics (Andra, SCK/CEN, ONDRAF/NIRAS)
- *Specific design provisions* to avoid or mitigate certain sources of uncertainty, and ample margins to counter their effects (e.g. avoiding problematic materials (IRSN), durable containers, limiting temperatures (SCK/CEN, Andra, Enresa, ONDRAF/NIRAS, SKB), compartmentalisation of the repository into zones to prevent interactions (Andra).

The discussions on this issue revealed a large consensus on the majority of the points above, but some organisations did not assign themselves to some of the points as they do not have yet clear views on them, or work in those areas has not been carried out yet in their programme.

13.4.2 Uncertainty treatment

The treatment of uncertainty in the safety assessment needs a systematic and structured approach clearly established in the project basic strategy and implemented following strict procedures. The whole process of uncertainty analysis has to be thoroughly reported. QA and expert review are essential for building confidence in the analysis.

The basic Strategies for handling uncertainty tend to fall into the following broad categories (NDA):

- Demonstrating that the uncertainty is irrelevant, i.e. uncertainty in a particular process is not important to safety because, for example, safety is controlled by other processes.
- Addressing the uncertainty explicitly, for example using probabilistic techniques.
- Bounding the uncertainty and showing that even the bounding case gives acceptable safety.
- Ruling out the uncertain process or event, usually on the grounds of very low probability of occurrence, or because other consequences, were the uncertain event to happen, would far outweigh concerns over the repository performance (for example a direct meteorite strike).

- Explicitly ignoring uncertainty or agreeing a stylised approach for handling an uncertainty (for example the 'reference biospheres' approach developed by the IAEA BIOMASS project).

In France the management of uncertainties is at the centre of the safety analysis [Andra, 2005]: "Qualitative safety assessment (QSA) methodology was developed for detailed consideration of FEPs in the Dossier 2005 Argile. The qualitative safety analysis is a method for verifying that all uncertainties in particular in FEPs and design options have been appropriately handled in previous steps of the analysis, thereby justifying post hoc, e.g., the selection of altered evolution scenarios. It also led to the identification of a few additional calculation cases and has, in principle, the potential to inform design decisions and the derivation of additional scenarios. Some uncertainties can have a direct influence on the confidence that can be had in a given safety function. For example, if the uncertainty about the permeability of the host formation is too great, this could call into question the performance of the function «prevent water circulation». Uncertainty is the subject of a systematic study that identifies:

- which component is concerned by this uncertainty, with if relevant the effects caused by one component on another by means of a perturbation;
- which performance aspects of which safety function can become altered. A qualitative, but argued assessment, including the use of special calculations if relevant, is conducted on the risk of a significant reduction in the expected performances ;
- if applicable, and if such information is useful, the time period involved"

Sensitivity analysis is a tool generally utilized in the uncertainty treatment to investigate the significance of the different uncertainties (see chapter 14). The main objective is to prioritize the uncertainties for future work. But the problem lies often in the characterisation of the uncertainties, which may prove to be extremely complex. So, it is sensible to try simplified strategies first to reduce the problem.

In some occasions it may be shown that a particular uncertainty is irrelevant because either it is unlikely, or because the impact is not significant. Both strategies may be used in combination. The later may be done, for example, by considering an extreme assumption for the uncertain element (the scenario, model or parameter), and verifying that the influence on the outcome of the assessment is not significant. This strategy must be applied carefully, making sure that the assumption made is conservative.

In other cases, the uncertain element may be represented in the assessment by a conservative assumption (e.g.: a conservative model, a conservative parameter value, a pessimistic scenario).

It may be interesting to combine detailed uncertainties in an uncertainty at a higher level, which encompasses all of them, for example, assuming the total or partial loss of a safety function. In the case of the engineered components, in a first assessment stage, uncertainties may be bound by postulating deterministic failures of these components with varying degrees of severity.

The approach to uncertainty analysis may be either essentially deterministic, as it is the case in many countries of continental Europe, or probabilistic, as it is the case in particular in the US and UK. In some probabilistic safety assessments each scenario is assessed separately, and its probability is not quantified (Enresa). In fully probabilistic approaches, the probability is thoroughly considered and mathematically aggregated with uncertainty.

In both deterministic and probabilistic approaches, conservative assumptions are often made to deal with uncertainties. “In performance assessment modelling, it is often necessary to make a number of simplifying assumptions, either because insufficient data are available or the modelling capability cannot represent some feature of the system in full detail. The aim is to address issues as realistically as possible, whilst erring on the side of caution. Therefore, some simplifications involve taking a conservative view, i.e. assumptions are made such that radiological risk will tend to be over- rather than under-estimated. Conservative assumptions are often the best way of addressing issues without introducing unnecessary complexity into the models.

However, this approach of making conservative assumptions can sometimes lead to models which, although robust from a safety point of view, are physically unrealistic. Also, it is important to note that the probability that all parameters in a system take their most pessimistic values is, in general, negligible, so that a calculation that assumes this would give a significant overestimate of the consequence and therefore provide a poor basis for making decisions. In particular, when optimising the design of a repository, it is important to have as realistic a view of the repository system performance as possible” (NDA).

The methods used in the treatment of uncertainties in the safety assessments are, in general, specific for each type of uncertainty. In the discussion which follows, the terminology used in [Galson, 2007] is used, but the actual classification of uncertainties made by the different organisations must be borne in mind.

13.4.2.1 Scenario uncertainty

Systematic scenario methodologies address directly the issue of scenario uncertainty, and are described in Chapter 8 “Definition and assessment of scenarios”. A sufficient set of scenarios has to be defined in order to encompass the range of plausible future evolutions of the repository system.

One important issue for scenario analysis is comprehensiveness, in particular, the consideration of all relevant factors (FEPs). In many programmes, this is verified by using FEP databases (preferably site specific) in the construction of scenarios. The FEP database itself has to be comprehensive; diverse measures are taken to secure this: use of expert judgement, peer review, audit against international established FEP databases (e.g. the International FEP Database and the FEPCAT of OECD/NEA). In Enresa’s assessments several independent teams of experts constructed independent lists of FEPS relevant for the formation of scenarios. In Andra’s methodology, scenarios are formed on the basis of systematic structured analyses of the phenomena affecting the repository system (PSARS); the resulting scenarios are compared later with the results obtained with Qualitative Safety

Assessment following a FEP database based approach; both approaches are developed by different expert teams.

In safety assessments one (or a few) scenario(s) is defined to describe the most likely evolution of the repository; this is called in different ways in the different programmes: reference scenario, normal evolution, base scenario, etc. This scenario(s) may be complemented by several cases which address alternative likely evolutions (e.g. in the Belgian programme, this is done for alternative future climatic evolution; these alternative cases are called “variants”).

Several scenarios are usually selected which address the unlikely evolutions (“altered scenarios” in [Andra, 2005]) or are defined pessimistically to encompass the uncertainties in future developments. The latter receive sometimes names as “worst case scenario” (GRS-B) or “very degraded” scenario [Andra, 2005].

The definition of the scenarios needs several categories of information, each of which is the subject of uncertainty: i) the initial conditions, ii) the internal FEPs and the couplings among them, iii) the external FEPs, iv) the time scales where the various elements of the scenario definition are relevant.

Andra’s “qualitative safety assessment (QSA) consists of identifying uncertainties and studying their influence on repository evolution, thus analyzing the limits of validity of the given scenarios”.

In [SKB, 2006] the purpose of the methodology is “the selection of a sufficient set of scenarios, through which all relevant FEPs are considered in an appropriate way in the analysis. The selection of scenarios is a task of subjective nature, meaning that it is difficult to propose a method that would guarantee the correct handling of all details of scenario selection. However, several measures have been taken to build confidence in the selected set of scenarios:

- a structured and logical approach to the scenario selection;
- the use of safety function indicators in order to focus the selection on safety relevant issues;
- the use of bounding calculation cases to explore the robustness of the system to the effects of alternative ways of selecting scenarios, including unrealistic scenarios that can put an upper bound on possible consequences;
- QA measures to ensure that all FEPs have been properly handled in the assessment;
- the use of independent reviews”. [NEA, 2007]

Sensitivity analysis is used to check the importance of the different elements that characterise the scenarios. “What if” scenarios are often used to analyse the significance of scenario attributes. In some programmes, bounding scenarios are defined.

It is important not only that all relevant factors are considered and appropriately represented. Their intensity and time of occurrence have also to be adequately described (SCK/CEN ONDRAF/NIRAS).

In general it may be difficult to quantify the probability of unlikely scenarios. It may not be necessary to quantify probability, for example, if the assessment shows that the consequences are acceptable. But in other cases that result in non-negligible consequences, quantification may be required to show compliance with the regulations. In a fully probabilistic approach the scenarios and scenario attributes are defined probabilistically.

In some cases, of extensive irreducible uncertainties, some scenarios are defined in a “stylized” manner, applying logical decisions, based on expert judgement or in regulatory guidance. This is especially the case for human intrusion scenarios. The same approach is often taken for the description of the biosphere in the different scenarios.

13.4.2.2 Model uncertainty

The quantification of the system evolution and performance requires the use of models that allow its mathematical representation. This itself is a source of uncertainty, due to:

- poor or incomplete knowledge or understanding
- simplified or incomplete representation of the system or processes
- human errors in the execution of the models (SKB in [NEA, 2007])

One issue which has to be addressed is the influence between processes (i.e. couplings). The ignorance or misrepresentation of the mutual influences between processes is a typical cause of model uncertainty.

The handling of model uncertainties requires the use of structured procedures. Uncertainties are identified by assessing the level of knowledge achieved for the different models used in the assessment. This is usually done in the first instance by the scientific experts and by the safety assessment experts involved in the programme development, and in a second instance by external experts, peer reviews, etc. Comparison of laboratory, in situ experiments or natural analogues with *blind* simulation results, is an important way of testing models and of evaluating the confidence in quality. The latter process of confidence building is often referred to as “validation”. (SCK/CEN ONDRAF/NIRAS).

Several possible options are open to deal with model uncertainties:

- The use of good models i.e., verified, checked against experimental evidence, based on expert judgement, benchmarked, well documented.
- The use of alternative plausible models. As an example, in the U.S. Yucca Mountain Project, “a structured approach has also been established to take account of alternative conceptual models (ACM). If two or more ACMs show different subsystem performance, abstractions are developed for both and used in TSPA calculations to determine any differences in system-level performance. If there are significant differences, the options

are to include multiple ACMs in TSPA with a weighting, or to consider a conservative choice of model" [NEA, 2004b].

- The use of conservative or bounding models. These may be highly simplified models, in some cases just parameters, for which the uncertainty may be defined (ranges, pdfs) (Posiva and GRS-B).
- In the case of highly complex external phenomena, by the use of stylized approaches (e.g.: SKB treatment of conceptual uncertainty for external influences, essentially through the definition of a sufficient set of scenarios and by state-of-the-art models) [NEA, 2007].
- Some conceptual uncertainties (such as certain uncertainties on site characteristics) may be handled as alternative scenarios (e.g., alternative discharge zones, unknown discrete features).

Human errors in the handling of models may be avoided by a number of measures:

- Good documentation of the model and of the computer code where it is implemented (for example, specifying the domain of validity).
- Formal procedures to guide and control the use of the models in the safety assessment
- Comparing the results obtained with simplified models (e.g. "scope calculations")
- By the use of QA procedures, peer review, benchmark exercises, etc.

13.4.2.3 Parameter uncertainty

Parameter uncertainty is addressed in most if not all safety assessments, even in the programmes at an early stage of development. Parameter uncertainty may arise for different reasons:

- The value is dependent on conditions not well established
- Insufficient knowledge
- Data is dependent on circumstances external to the repository or on future decisions (e.g. inventory, waste characteristics, technological options)
- Inaccuracies in measuring techniques
- The value in the future may change
- Natural variability (aleatory); values only known at discrete places that have to be extended to larger domains
- Measurements are taken in a context different to the repository system (e.g. in experiments)
- Not well established correlations between data

The treatment of parameter uncertainty in the safety assessment may be either deterministic or probabilistic. The choice of one or other approach is primarily dictated by regulations. When the regulatory acceptance criterion is expressed in terms of risk, or the probability and the consequences are required to be aggregated, the approach must be probabilistic. When the regulatory criterion is dose, a probabilistic approach may be useful in the analysis of uncertainties; i.e. it can give an indication of the range of the expected doses; deterministic based programmes often use probabilistic methods as a complement to deterministic ones [NEA, 2007].

Probabilistic methods (e.g. Monte-Carlo) for data uncertainty treatment (including spatial variability) process uncertainty characterised inputs (e.g. pdfs). In some programmes the number of uncertain parameters is reduced, in order to facilitate the calculations (GRS-B and NRI), in particular to reduce the computing time; this is done through a screening process (NRG) where some parameters, for example those for which uncertainty is not influential and are not correlated with other uncertain parameters, are treated deterministically (e.g. they are assigned a conservative value). In some occasions the uncertainty of the parameters may be based on the data available (for example on the basis of statistical distributions), but very often expert judgment (formal or informal) is needed (see chapter 12 "Criteria for input and data selection").

Care is needed to identify and avoid "risk dilution"; this effect can be identified by comparing the peak of the calculated mean (dose or risk) (for each point in time) with the mean of the individual peaks (irrespective of the time they occur) [Galson, 2007].

The results of probabilistic calculations are shown by means of different statistics: percentiles, peak value, mean, median, etc. In a fully probabilistic assessment, the results for the various scenarios are aggregated, considering their probability. The results may be presented in the form of risk, or expected dose (probability weighted mean dose). In German and US (WIPP Project) studies performed in the past, the complementary cumulated density function (CCDF) for the maximum was plotted. That means that the maximum output values of all runs, regardless of their time of occurrence, are evaluated together. Plots of maxima frequency density have also been used (GRS-B)

"The programmes in the US have played a significant role in the development and use of probabilistic methods for conducting PA. For example, PA calculations for the WIPP project involve using the results from a set of deterministic, process-level models to construct response surfaces that are subsequently used by a probabilistic, process-level code (CCDFGF) to estimate potential releases [DOE 1996]. Uncertainty in the process-level models is considered epistemic and is associated with the lack of knowledge about the precise values of the model parameters. This uncertainty is represented by sampling 300 sets of parameter values (using Latin Hypercube Sampling) for the parameters and running the models for each set. PDFs for each parameter are derived from data, where available, and/or by using subjective methodologies. The level of information on which to base the assignment of the distributions of possible values varies greatly among the parameters. The level of knowledge is an important consideration in assigning both the shape and the variance of a distribution. When knowledge about parameters is small and these parameters have been identified by the regulator or modellers as potentially significant to the performance of the disposal system, a conservative approach is sometimes taken. Bounding assumptions have been made in these instances" [Galson, 2007].

In the U. S. Yucca Mountain project, “internal and external (including international and regulatory) reviews of the earlier TSPA that supported the Site Recommendation considered that there was an inconsistent treatment of uncertainties across the disciplines feeding into the TSPA. The project’s response to these reviews was to prepare an “Uncertainty Analysis and Strategy” document and guidance. The overall goal of the uncertainty strategy is an analysis approaching realism. However, the focus on a realistic treatment of uncertainty is not necessarily the same as a full understanding of realistic performance. It is therefore appropriate to use simplified models, broad uncertainties and conservatisms providing these are justified and explained. A team approach of scientists and analysts is a key element of the uncertainty strategy. A formal process has been established for selecting parameter values and distributions for TSPA. For uncertain parameters that are important to system performance, the goal is to represent the “full range of defensible and reasonable parameter distributions rather than only extreme physical situations and parameter values”. [NEA, 2004b].

In the deterministic calculations the probability is not aggregated with the calculated indicators. In some occasions, calculations are just done for one parameter value (e.g. conservative values) and the effects of uncertainties are discussed in a more qualitative way. Conservative values cannot always be straightforwardly established (GRS-B). Often in deterministic approaches the calculation of the indicators is repeated for one single scenario using several sets of input data, intended to represent the domain of uncertainty. In this approach, the results are series of values of the calculated indicators, which are not aggregated each other. (IRSN).

In some programmes, parameter uncertainty is handled explicitly at both a detailed (process) level, and at an integrated (e.g. global safety assessment) level. The traceability of uncertainties from individual elements to the overall safety assessment should be made transparent to build confidence in the Safety Case (Posiva). In other programmes, parameter uncertainty is more informal at the process level (e.g., only “best estimated” or “conservative” calculations are made) and the formal comprehensive treatment of parameter uncertainty is reserved for the integrated safety assessment.

13.5 Applications and experience

There is extensive experience in the application of uncertainty analysis methods to safety assessment. In the most advance programmes, the analysis of uncertainty is documented in safety assessments made in compliance with legal requirements and submitted to the scrutiny of regulatory authorities. The NEA project INTESC [NEA, 2006] gives ample attention to the experience gained in the treatment of uncertainty in the safety case.

In France (Andra) the management of uncertainties is at the centre of safety analysis of the Dossier 2005 Argile. The QSA methodology was developed specifically for Dossier 2005 Argile. It was based on previous attempts and on the comments that these attempts generated, especially from the 2003 NEA peer review of “Dossier 2001 Argile". The aim was to provide traceability in the management of uncertainties. The reader of Dossier 2005 Argile, and especially safety evaluators, have a direct access to a list of the uncertainties that have been managed in the dossier, explaining how they have been treated and what consequences they might have on safety. This proved useful when discussing the management of uncertainties with the various evaluators. The approach of Dossier 2005 to uncertainty analysis is deterministic.

In Sweden, ”the current safety case is a preparatory step for a safety case in support of a licence application”. The strategy applied for the management and treatment of uncertainty is documented in “several reports produced in the SR-Can assessment project (…) All these are primary references of central importance for the assessment and are published together with the SR-Can main report: [SKB, 2006]

- Data report
- FEP report
- Initial state report
- Process reports
- Climate report
- Model summary report
- FHA report. (deals with future human actions) ”

Most of the calculations in SR-Can are deterministic. Probabilistic calculations are used essentially as a means of handling data uncertainty and spatial variability in the modelling of radionuclide transport and dose”. [NEA, 2007]

ONDRAF/NIRAS and SCK/CEN have a long experience in the application of probabilistic methods in uncertainty analysis. In the PAGIS safety assessment, in the late eighties, a first series of limited uncertainty analyses were conducted, mainly focussing on parameter uncertainty by making stochastic calculations, and on the analysis of a first set of scenarios, derived on the basis of expert judgement. In the SAFIR 2 report [ONDRAF, 2001] more detailed uncertainty and sensitivity analyses were conducted and a first attempt in the direction of uncertainty management was made to discuss in a more systematic manner the different types of uncertainties and their impact on the level of confidence in the safety and feasibility of the studied disposal system and on the future activities of RD&D. SAFIR 2 led to a positive conclusion on the feasibility and safety, but also to the identification of the key remaining uncertainties and of the main priorities for the current RD&D phase of the disposal programme.

Enresa’s probabilistic approaches to uncertainty analysis have been implemented in the safety assessments Enresa 2000 and Enresa 2003, for repositories in granite and in clay, respectively. Each scenario is analysed individually; the results are expressed in terms of mean dose. All the scenarios fulfil the dose constraint (10^{-4} Sv/year) proposed by the Safety Authority (CSN). There has been no attempt to quantify scenario probabilities.

In Germany, GRS-B has a long experience in probabilistic safety analysis, which was carried out for the Pagis study. In later studies it was applied in the same form and using the same tools, recently for the LAW repository near Morsleben (ERAM) and the experimental LAW/MAW repository in the salt mine at Asse.

The probabilistic approach is used to address most of the uncertainties in NDA's post-closure assessments of the radiological risk from the groundwater pathway. Nirex's Generic post-closure Performance Assessment (GPA) does not consider time-dependencies explicitly. Rather, the possible variation of a parameter in time is included implicitly in the uncertainty (in probabilistic calculations) for that parameter. Some stakeholders have challenged this approach and dynamic models will be used in future assessments.

In the late 1980's the VEOS study (Safety evaluation of disposal concepts in rock salt) has been performed in the Netherlands, which used a scenario approach followed by a deterministic consequence analysis and several deterministic sensitivity studies. For some scenarios with a relatively high exposure the probability of occurrence was also calculated. In the early 1990's a generic probabilistic safety analysis of the Dutch generic reference disposal concept has been performed. The results obtained show that for well-designed disposal systems, quantitative use of uncertainty (e.g. by probabilistic analyses) generally leads to the observation that for all different scenarios regarded in the uncertainty study, the regulatory limits for dose and risk are met (NRG).

Due to the initial stage of deep disposal programme in the Czech Republic, the total performance assessments were based on simplified, deterministic models. Only the effect of limited number of parameters (e.g. solubility) has been also tested in probabilistic mode. It was concluded that both sensitivity or "what-if" deterministic analyses and probabilistic analyses could contribute to demonstration that all uncertainties have been taken into account in safety assessments. For calculating the uncertainty of migration parameters (such as distribution coefficients Kd), an approach that stems from chemical analytical measurement calculations has been applied (NRI) .

13.6 Developments

The development of methods and tools to improve the treatment of uncertainty in safety assessments is actively pursued in practically all the national programs and is in the focus of international programmes. The Pamina Project RTDC2 "Treatment of Uncertainty" focused entirely on uncertainty methods and strategies.

In France, the different national and international peer reviews of the Dossier 2005 agreed that the QSA method appeared to be an interesting tool, and was quite efficient at managing uncertainties. However, it was recommended to better explain such a method, especially the link between QSA, Safety Functions, and PARS. It was also suggested to develop the QSA method ahead of the "definition and description" of the scenarios. On going work will include feed back on this methodology, and exchange on an international level, in order to consolidate for the future safety assessments that Andra will have to produce, not only for the on-going geological repository project, but also for other future projects or existing disposal facilities (Andra).

Also in France, a new version of the relevant safety rule [JORF, 1991] is currently in progress, to account for the developments accomplished in Andra's Dossier 2005. IRSN explores the possibility of deriving simplified models from the 3D model in order to perform probabilistic analysis. A probabilistic approach is judged by IRSN to be complementary to the deterministic modelling approach, which remains the reference approach. IRSN develops studies aiming at evaluating the means for predicting the performances actually reached in situ by the engineered components which depend on the initial and real state of the components reached after the construction and the operational phase.

In Germany, it is planned to create a basis for more systematic uncertainty management. This comprises unique rules for establishing appropriate probability distribution functions according to the degree of knowledge, as well as applying standardised criteria for evaluation of the results (GRS-B).

In the U.K., NDA has an on-going programme of work to develop the treatment of uncertainty as the safety case is developed for the forward programme. NDA continues to keep a watching brief on developments in the treatment of uncertainty to ensure awareness of new methodologies and their possible application. For example, collaboration with Bristol University on the application of Bayesian Belief Networks to variant scenarios connected with climate change has been carried out recently. Future assessments will use a more sophisticated treatment of the time-variation of parameter values, rather than treating time variation within parameter uncertainty.

In the Czech Republic, NRI experience has shown that the best way to express uncertain data is using probability distribution functions (pdfs), but it is felt that this approach makes it difficult to explain the results in a simple way. For this purpose, it seems to be more convenient to apply variation sensitivity analyses. Therefore in future analyses it is proposed to use both probabilistic and deterministic approaches.

In Finland, Posiva is developing methods for a systematic treatment of uncertainty.

ONDRAF/NIRAS is developing a new safety strategy methodology in order to treat the uncertainties (of all classes) in a more systematic and pragmatic way.

13.7 Conclusions

The regulations and guidance at both international and national levels identify the need for a systematic and structured management of uncertainties in the repository development programmes, and require their treatment in the safety case.

The national agencies and research organisations responsible for the repository development programmes have recognised the importance of these requirements, and have devoted since early stages in their programmes significant effort to develop and implement appropriate measures and methods to deal with uncertainties. Experience has been gained in the application of uncertainty analysis methods in safety assessments. In the most advanced programmes, the treatment of uncertainties in recent published safety assessments has reached a high level of maturity and comprehensiveness.

Both probabilistic and deterministic methods are available for uncertainty analysis. The choice between them is primarily driven by regulations. Many programmes consider that these approaches complement each other. More generally, in several programmes alternative methods are applied in parallel to increase the confidence in the results obtained.

Aspects deserving further efforts have been identified in the various programmes. They are being actively pursued within national and international R&D programmes, in particular within Pamina RTDC2.

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14. Sensitivity analysis

14.1 Introduction and background

In the field of numerical performance assessment for radioactive waste repositories, sensitivity analysis plays an increasingly important role. Due to the large time and space scales involved it is unavoidable that models and parameters used for a long-term prediction of consequences are subject to a considerable degree of uncertainty. In general, uncertainties can be classified in two categories:

- *Aleatory uncertainties* are due to random influences on the system. They cannot be reduced, except by modifying the concept and systematically avoiding such influences.
- *Epistemic uncertainties* result from our incomplete knowledge about the system and its parameters. Such uncertainties can be reduced by means of targeted investigation, improved measurements or optimised construction.

Aleatory and epistemic uncertainties are sometimes hard to distinguish and in most cases, there are characteristics of both types. The sorption parameters of a transport path, for example, are mainly subject to epistemic uncertainty, since the exact values are hard to determine, but there is also an aleatory aspect, as the path itself may depend on an unforeseeable geological evolution. On the other hand, the uncertainty of canister lifetime, which is aleatory by its character, can be reduced by applying specific production procedures or using specific materials; so it is epistemic in a certain sense. Therefore, although aleatory and epistemic uncertainties should be handled differently, they are often not distinguished.

It is of general interest to identify to what degree the uncertainty of the model output results from the input uncertainties. This is called uncertainty analysis. It allows the probability of exceeding specific limits under the influences of uncertain parameters to be assessed. Uncertainty analysis is treated in chapter 13 and is not further addressed here. Another question, however, is the sensitivity of the model to variations of individual parameters. This is important for identifying parameters that need specific attention to reduce the output uncertainty, which is predominantly relevant for epistemic uncertainties. Such investigations are called sensitivity analysis.

It is convenient to distinguish between deterministic and probabilistic sensitivity analysis. In a deterministic analysis, one or more parameters are varied between a few values and the model response is analysed. In a probabilistic analysis, however, a large number of model runs is performed with parameter values that have been drawn according to their statistical distribution using an appropriate sampling method. The evaluation of the output values is done using specific techniques and gives an insight to the sensitivity of the model to the uncertainties of the different parameters.

Another distinction can be made between local and global sensitivity analysis. While in a local analysis, only the close vicinity of a specific point in the parameter space is investigated, a global analysis comprises the entire parameter space. Often, deterministic investigations are used for local analyses and probabilistic calculations for global ones. This is, however, not a strict rule, since deterministic global methods exist and probabilistic local investigations are possible as well.

In the field of performance assessment for radioactive waste repositories, sensitivity analysis is an important part of the safety case. Local investigations are normally used for improving system understanding. The complex interactions between the parameters, however, can only be investigated using global sensitivity analysis. A number of methods and tools are available for this purpose. During the last few decades modern mathematical methods for sensitivity analysis have been developed that are better suited for nonlinear and non-monotonic models, like the variance based methods. Currently, the application of such methods to repository models is being investigated in a number of countries.

This chapter summarises the national activities in the field of sensitivity analysis for final repository models.

14.2 Regulations and guidelines

The regulatory requirements concerning sensitivity analysis (SA) studies for radioactive waste repositories are different across the European countries. Generally, the regulations are not very specific. Several countries are currently developing new guidelines.

In **Germany**, at present no legal regulation exists which demands a SA in the framework of a safety case. However, a new guideline is in preparation, which will contain such regulations. The proposal made by GRS-Köln demands SA in the framework of site specific safety analyses as a basis for the layout design of the repository system. SA is also required as a part of the performance assessment to demonstrate long-term safety in the safety case. Although no details are prescribed concerning the SA method to apply, the task of dealing with data uncertainties in the final evaluation step of the assessment points to global SA.

In the guide issued by the State Office for Nuclear Safety of the **Czech Republic**, for the preparation of a safety report for site licensing of DGR in February 2004 it is mentioned that the uncertainty of results should be evaluated by means of sensitivity analysis.

In the **United Kingdom** relevant agencies published updated guidance in February 2009 [EA, 2009], known as the ‘Guidance on Requirements for Authorisation’ (GRA), which explains environmental regulatory expectations for an application for an authorisation under the Radioactive Substances Act 1993 in the UK for the specific case of land based disposal of solid radioactive waste (a repository). The GRA includes the requirement “The overall safety case for a specialised land disposal facility shall not depend unduly on any single component of the case.” Although sensitivity analysis is not required explicitly by the GRA, this requirement indicates that sensitivity analysis may be required to show that a safety case is not depending unduly on any single component. The GRA also places a strong emphasis on the importance of optimisation, which may also be supported by sensitivity analysis.

In **France** there is the Basic Safety Rule 3.2.f as guidance for defining the situations providing demonstration of safety through evolution scenarios. A new version of this was released in 2007 in order to introduce the notions and the safety approaches developed in the 2005 Clay Dossier. It requires the most important parameters to be identified by means of sensitivity studies.

In **Belgium**, **The Netherlands**, **Finland** and **Spain** there are currently no detailed regulations concerning SA for final repositories. In Belgium regulatory requirements and guidelines concerning long-term safety of geological repositories for the disposal of high-level and long-lived radioactive waste are in preparation.

14.3 Terminology

There is not much discrepancy in the use of terms relating to sensitivity analysis between the participating organisations.

From a mathematical point of view, Saltelli [Saltelli, 2000] gives the definition:

<u>Sensitivity analysis (SA)</u> is the study of how the variation in the output of a model can be apportioned to different sources of variation, and of how the given model depends upon the information fed into it.

The IAEA Safety Glossary [IAEA, 2007] gives the following definitions:

<u>Sensitivity analysis:</u> a quantitative examination of how the behaviour of a system varies with change, usually in the values of the governing parameters.

<u>Uncertainty analysis:</u> an analysis to estimate the uncertainties and error bounds of the quantities involved in, and the results from, the solution of a problem.

Most organisations stick more or less to these definitions.

SCK/CEN and ONDRAF/NIRAS emphasise more precise definitions in the context of high-level radioactive waste disposal, aiming at the influences of all kinds of uncertain “elements” (parameters, assumptions, simplifications).

Andra introduces the concept of a “reference calculation” and single- or multi-parameter “sensitivity analyses”. The former defines the standard case, made up from best knowledge about the foreseeable system evolution, while the latter means a series of studies investigating the influences of the individual parameters.

GRS-Braunschweig distinguishes between deterministic SA and probabilistic SA, the former used for showing how the system reacts to variations of specific parameters and the latter addressing the behaviour of the system under variation of all parameters according to their distributions. Moreover, a distinction between global and local sensitivity analysis is made.

The concepts of sensitivity analysis are based on different approaches and techniques. Most organisations apply correlation- or regression-based methods, which are closely interrelated and yield similar results. Another type of method is nonparametric SA, which allows statistical tests of the relevance of parameter distributions to the output distribution. Variance-based SA has the advantage of providing quantitative sensitivity measures even for highly nonlinear systems.

14.4 Methodology

Deterministic SA is used to investigate the reaction of the model under variation of single parameters, model modifications, scenarios or assumptions. It is therefore a good tool for analysing the sensitivity of the system against all kinds of uncertainties and helps to gain understanding of the functioning of the system.

Probabilistic SA is mostly used to analyse the model sensitivity against parameter uncertainties. Usually it is performed as a global analysis by varying all relevant parameters simultaneously and taking into account possible interdependencies. Model uncertainties can also be included by mapping them to a specific parameter that is varied between discrete values.

A probabilistic approach to sensitivity analyses consists of two steps. Firstly, a number of runs of the system model, for which the parameter values are sampled at random, are calculated. Secondly, various techniques can be used to analyse the results of those calculations. The methods presently applied in the field of probabilistic sensitivity analysis for final repository models can be categorised in four groups:

- correlation and regression methods,
- non-parametric statistical test,
- variance-based methods,
- graphical methods.

14.4.1 Correlation and regression methods

These methods are based on an analysis of the linear correlation between the model output and the input parameters, or on the calculated influences of the individual input parameters to a linear regression of the output values. Both kinds of methods are closely interrelated and yield similar results. They have in common that they are most suitable for models with a close-to-linear behaviour. This can be checked by calculating the coefficient of model determination, R^2. It describes which proportion of the output variability can be explained by linear influences of the input parameters and should not be below 0.5 to allow the assessment of a model using correlation or regression methods.

If the model under investigation is highly non-linear, correlation or regression methods do not perform very well. If, however, the model is at least monotonic, the coefficient of model determination can be considerably increased by means of a rank transformation. This transformation replaces the numerical values of each input parameter and of the model output of a multi-run calculation by their ranks in an ordered list. Monotonic relations are thereby transformed to linear relations. Correlation or regression methods applied to a rank-transformed set of parameters and model output normally yield more robust and reliable results at the cost of losing their quantitative meaning. A rank-based evaluation produces a ranking of the parameters according to the system sensitivity, but is inadequate for comparing them on a fully quantitative basis.

Calculating the linear correlation coefficients between the model output Y and any input parameter X_j yields a measure for the sensitivity of the model to variations of the respective parameter. These coefficients are named after Pearson (PEAR). A positive coefficient means that the result increases if the parameter does so, a negative value indicates an inverse correlation. A correlation coefficient of 1 or -1 means a strong linear direct or inverse relationship between input and output. If the coefficient is 0 the parameters are uncorrelated, which means that the output shows no linear dependence on the input. This does not necessarily mean that the model is insensitive to the parameter, although it is normally interpreted in this way. If applied on a rank basis, the correlation coefficients are named after Spearman (SPEA). Spearman's rank correlation coefficients are a good means to assess the sensitivity of parameters, but it should be noted that the rank transformation largely destroys the quantitative meaning of the calculated measures, as it reduces the quantitative difference between two values to a simple "higher-or-lower" decision. The higher the absolute value, the stronger the relationship between input parameter and model output, but no statement about the slope of this relationship can be made.

Linear regression is based on the attempt to represent the model under analysis, as well as possible, by a linear estimator. The coefficients of the individual parameters are calculated such that the total square error of the estimator is minimised. They provide measures for the sensitivity of the model against the individual parameters. To allow a unified assessment of these values, the parameters are transformed such that they get the expectation 0 and the standard deviation 1. Then the coefficients are called standardised regression coefficients (SRC). Like the correlation coefficients they are always in the range between -1 and 1, where the absolute value 1 is only reached in the case of a strong linear relationship. The same concept applied on basis of ranks leads to the standardised rank regression coefficients (SRRC). The advantages and disadvantages of this procedure are the same as for the use of correlation coefficients.

The coefficient of model determination, R^2, is defined as the correlation coefficient of the values estimated by the regression model and the real values. If it is close to 0, the estimation is rather poor, whereas a value near 1 indicates a close-to linear behaviour of the model and therefore a good performance of linear sensitivity analysis methods.

If the input parameters are correlated among themselves, accidentally or on purpose, their influences to the model output are coupled. The methods described so far are unable to resolve this coupling and describe the total influence of the input parameters including that resulting from couplings with other parameters. This problem can be resolved by constructing two linear regression models, one for the input parameter under investigation and one for the output variable, each with respect to all input parameters except that one under investigation. Then the partial correlation coefficient (PCC) is the ordinary correlation coefficient between the residuals of these two models. It is a measure for the model sensitivity to the parameter, reduced by the linear effects of all other input parameters. It can be shown that in case of uncorrelated parameters these values are identical to the SRCs. If applied on rank basis, this concept yields the partial rank correlation coefficients (PRCC), which, of course, are equal to the SRRCs in the case of uncorrelated parameters.

14.4.2 Non-parametric statistical tests

The basic idea of these methods is to separate the sample into two subsamples, according to some criterion, and to check whether the distributions differ significantly. Various methods based on non-parametric statistics have been tested [Saltelli, 1990]: Cramér-von Mises, Kruskal-Wallis, Mann-Whitney and Smirnov. The Smirnov test appeared to be the best performing non-parametric statistic. Its principle is as follows:

The total of all parameter sets of the sample is separated into two subsamples according to the 90%-quantile of the output. That means that the 10 percent of input parameter sets that lead to the highest output values are separated from the others. The distributions of the parameter under investigation in both subsets are compared with each other. If there is no significant difference, the model can be assumed to be rather insensitive to the parameter. The test is performed by calculating the maximum absolute difference between the empirical distributions of the parameter in both subsamples. The null hypothesis of equal distributions is rejected with significance α if this difference exceeds the 1-α quantile of the Kolmogorov distribution.

14.4.3 Variance-based methods

If the model under consideration is neither linear nor monotonic, which is often the case when dealing with complex repository structures, the linear methods perform rather poorly.

Variance-based methods [Saltelli, 2000] follow a different approach and do not require linearity of the model. The variance of a statistically distributed parameter is the mean squared deviation from its mean value. To assess the influence of a parameter Xj to the model output Y the expectance of Y is calculated under the condition that Xj remains constant. The variance of this value under variation of Xj is then calculated and divided by the total variance of Y. This value is a quantitative measure for the sensitivity of the output to the parameter Xj. It is called the first-order sensitivity index.

There are different methods to calculate the sensitivity indices. The most elegant way is given by Sobol's theory of decomposition of the total variance into terms of increasing dimensionality, which yields not only the first-order indices but also all higher orders, describing the influence of a parameter to the output in co-actions with other parameters. Of specific interest are the total-order indices, which take account of all possible parameter interactions.

Another method for calculating the sensitivity indices is the Fourier Amplitude Sensitivity Test (FAST) [Saltelli, 1997 and 2000]. The idea is to scan the parameter space by means of periodical functions with interference-free frequencies and to recover these frequencies in the model output by performing a Fourier analysis. Whereas the classical FAST yields only the first-order indices, the extended FAST method also calculates the total-order indices within the same evaluation.

14.4.4 Sampling

The procedure of generating a set of parameter values for calculation is called sampling. Some methods, such as Sobol and FAST, need specific sampling procedures that are adequate for the intended evaluation. FAST, for example, requires a periodic scan of the parameter space with well-defined frequencies, and there is only little room for randomness. The other methods mentioned here, however, are more or less independent of the sampling procedure.

The easiest and most popular sampling method is pseudo-random sampling. All parameters are drawn by simply using a numerical random number generator, initiated with some arbitrary seed number. It has to be made sure that the given parameter distributions are correctly taken into account by weighting the probabilities of specific value intervals. If statistical correlations of specific parameters exist they also have to be taken into account properly. Random sampling can be done by appropriate tools like SIMLAB [Saltelli, 2007]. A drawback of this method is that a large number of runs are required to ensure that the realisations sufficiently cover the total space of possible parameter values and their combinations.

Latin Hypercube Sampling (LHS) is an alternative sampling method that ensures, as well as possible, that the sampled parameter values are spread over the whole range of their distribution. It is based on the idea of dividing the parameter interval into sub-intervals of equal integral probability, such that each combination of sub-intervals is assigned the same probability. The sampling procedure has to make sure that all these pieces of the parameter space are equally populated.

14.4.5 Presentation of results

An adequate presentation of the results facilitates the interpretation of a Safety Assessment. Since the values of the calculated rankings, sensitivity estimators or sensitivity indices vary with time, they can be shown as a function of time. This is demonstrated in Figure 17 using calculations from the Belgian programme. The figure shows the most significant PRCCs of the stochastic input variables with respect to the total dose rate as a function of time for the activation and fission products. A similar example is given in Figure 18 showing the time-dependency of the first-order sensitivity indices in a German study, calculated with FAST. Two independent sets of calculations are compared, showing that there is still no satisfying robustness, even with more than 10,000 runs.

An example for presentation of the results of a deterministic sensitivity analysis is given in Figure 19, that has been taken from the Spanish study. A number of deterministic variants of the reference (or normal evolution) scenario have been calculated, changing a parameter value or using an alternative submodel. Peak doses in the 53 variants are represented together with the peak dose in the reference scenario. Variants are grouped together on the base of the repository compartment affected. Graphs like in Figure 19 can be done for the total dose or individual radionuclides and clearly show the parameters or parts of the repository that control the doses.

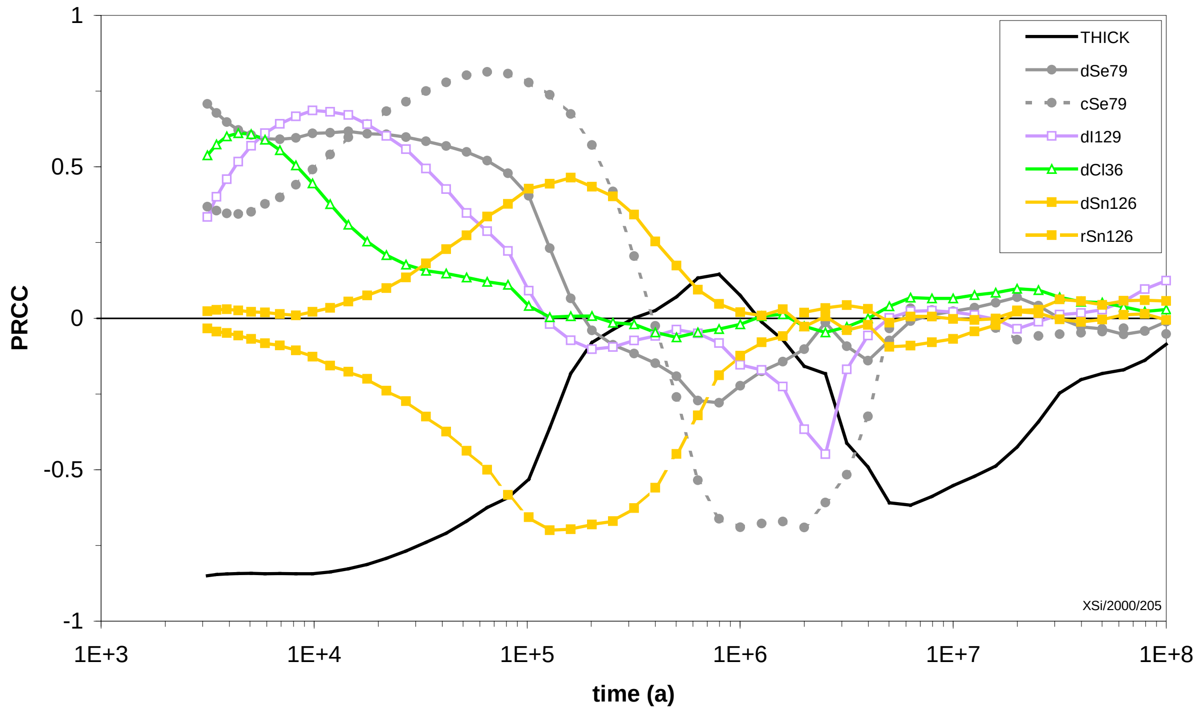

Figure 17 - Time-dependency of Partial rank correlation coefficients (PRCCs) of the most important parameters in a Belgian SA study: the effective thickness of the clay barrier (THICK) and the migration parameters of the activation and fission products to which the dose rate is the most sensitive (d: diffusion coefficient; r: retardation factor; c: solubility limit)

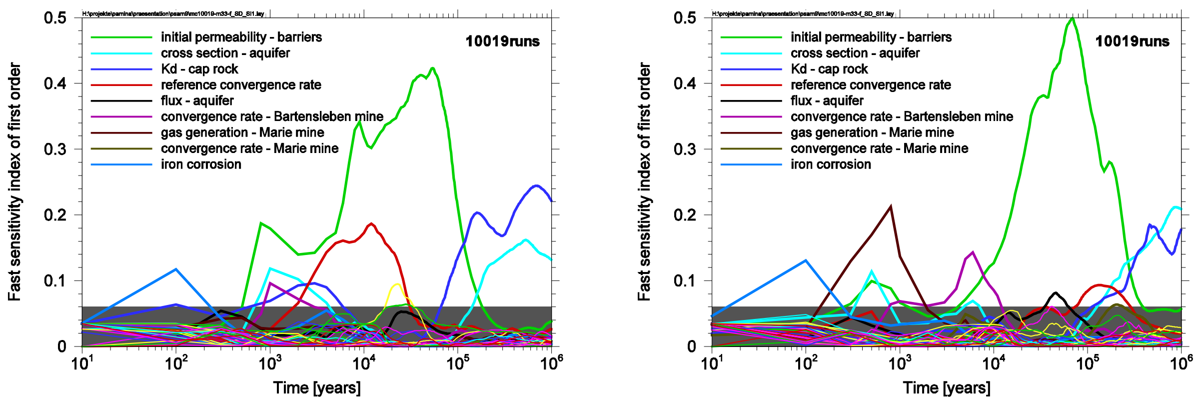

Figure 18 - Time-dependency of the first-order sensitivity indices, calculated with FAST in a German SA study. Two independent sets of calculations are compared.

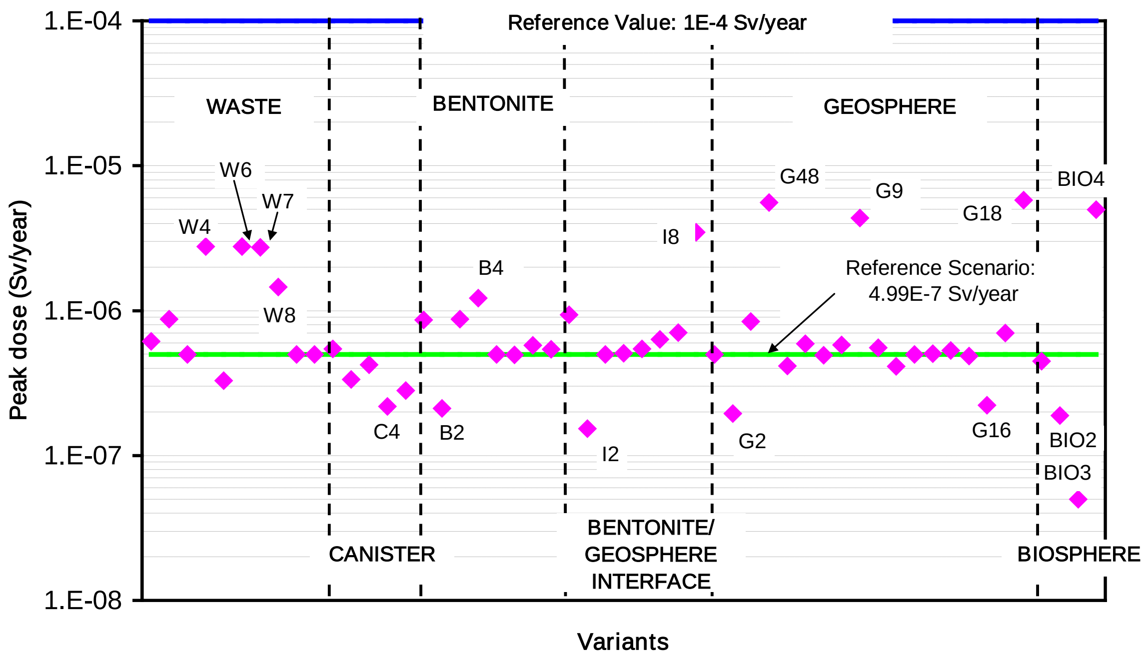

Figure 19 - Results of a Spanish deterministic SA study for the total dose. The variants are grouped according to the compartment of the system affected and show which compartments have a great effect on doses.

14.4.6 Graphical methods

There are a number of well-approved graphical methods of sensitivity analysis. These do not yield quantitative sensitivity measures and not even parameter rankings, but nevertheless yield valuable information by showing specific sensitivities of the system in a very descriptive way and on one sight. Scatter plots, cobweb plots and cumulative sample mean (CSM) plots should be mentioned here, although these techniques have scarcely been applied by the PAMINA partners. Scatter plots are easy to generate and show directly how the system reacts to the variation of a specific parameter. Cobweb plots and CSM plots are specific presentations that are adequate for illustrating the main influences on the model output in one figure.

CSM plots can provide sensitivity measures and parameter rankings. Using the maximum vertical distance of the cumulated contribution to the media to the diagonal an statistic that allows parameter ranking is obtained.

14.5 Application and experience

Enresa has performed a deterministic sensitivity analysis in its studies for the reference concept. 53 variants were defined changing parameter values or using alternative submodels. Variants were grouped on the base of the compartment of the repository system affected: 10 variants are related to the waste, 5 to the canisters, 8 to the bentonite buffer, 8 to the interface between bentonite and granite, 18 to the host formation and 4 to the biosphere. For the reference scenario and the 53 variants a probabilistic calculation was done, and the time dependent mean dose was obtained. The peak value of the mean dose is presented for the grouped variants, allowing to identify, which parts of the system have a stronger effect on doses (see Figure 19). Figures similar to 19 can be created for specific radionuclides and can provide useful information. For example, the waste-, canister- and bentonite-related variants produce significant changes in the dose due to ^{135}Cs but nearly no variations for ^{79}Se and actinides.

SCK/CEN and ONDRAF/NIRAS have performed several sensitivity analyses within the Belgian high-level waste programme. A first group of investigations, applied to the whole repository system, aims at the identification of the elements of the repository system that strongly influence the calculated doses [Marivoet, 1997]. They have contributed to understand the functioning of the disposal system and helped in developing a set of safety functions [De Preter, 2007]. A second group of applications is based on sensitivity analysis carried out for a specific part of the repository system. Evaluations of the impact of uncertainty in models or parameter values often belong to this group. The demonstration that simplifying assumptions are correct or conservative can also be based on this type of sensitivity analysis.

Sensitivity analyses with respect to model and scenario uncertainty mainly use a deterministic approach, comparing the results obtained with the alternative models or scenario variants. For sensitivity analyses with respect to uncertainty in parameter values a stochastic approach was often used. The preferred technique for parameter sampling is Latin Hypercube Sampling (LHS). A large number of possible techniques for sensitivity analyses, based on non-parametric statistics, correlation based techniques and techniques based on linear regression, were tested, which lead to the preference of partial rank correlation coefficients and standardised rank regression coefficients.

Andra introduced the concept of a “normal evolution domain” instead of a reference scenario with fixed parameter values. This concept takes account of the uncertainties of the expected evolution that remain in a “normal” range. In the Dossier 2005 Argile a number of deterministic sensitivity studies were performed within the normal evolution domain, addressing different parts of the model system. Some typical parameters of these parts were varied to study the model reaction. Moreover, four altered scenarios were considered, which were ensured to cover all possible situations. Several deterministic sensitivity investigations were performed on these alternative scenarios.

In addition to these results, a probabilistic study was carried out taking into account the simultaneous variation spectrum of the various parameters. It is, however, regarded as difficult to draw direct lessons from this type of assessment as it depends on the probability distribution functions that were adopted. The objective adopted by Andra at the stage of this initial methodological exercise is first and foremost to identify the parameters that, due to their uncertainty, have the greatest influence on the uncertainty of the result. This, however, is usually undertaken on a deterministic basis.

NRG has performed sensitivity studies for more than 20 years. Within the PROSA study [Prij, 1993] a comprehensive SA was done. Different techniques were used. The sensitivity and uncertainty analysis in PROSA was done for three different parts of the repository system: the salt compartment, the groundwater travel time and the dose conversion factors. A groundwater intrusion scenario and a subrosion scenario were analysed for the salt compartment. Three rank-based correlation or regression methods as well as the Smirnov test were applied, moreover an uncertainty analysis was performed. It was found that 100 simulations were required to yield stable results. The advective radionuclide transport was analysed independently within the PROSA study and the SA was done with a different tool (UNCSAM [Jansen, 1992]), calculating standardised and normalised regression coefficients. Some adjustments, such as logarithmic parameter transformations, were made to improve the applicability of the methods. The uncertainty and sensitivity analysis for the dose conversion factors was also performed with UNCSAM.

GRS-Braunschweig has performed sensitivity studies since the late 1980s. Traditionally, rank-based correlation and regression measures have been calculated. For about 10 years, however, GRS has also been investigating advanced techniques for SA. Experiments were made with FAST and Sobol, in order to get the problem of highly non-linear and even non-monotonic models under control. Within the ERAM performance assessment study for the LLW/ILW repository in Morsleben, a probabilistic uncertainty and sensitivity analysis with 2000 runs was performed and evaluated by calculating three rank-based sensitivity measures and the Smirnov test. These techniques resulted in ranking lists of the 43 parameters. Additionally, a FAST analysis was done on the same system with 10,000 runs. It showed that FAST does not perform very well on the system, which seems to be due to the quasi-discrete behaviour of at least one important parameter. Exercises with FAST and Sobol have also been performed on a generic SF/HLW repository model with a high probability of zero-output. It was found that in this case the performance of FAST is rather poor, too. Generally, however, the performance of variance-based techniques on such models seems to be improved by a modified log-transformation.

NDA performed a comprehensive deterministic sensitivity analysis within its last site specific post-closure safety case [Nirex, 1997]. Generic work carried out since then has not included such a systematic sensitivity analysis, although a large matrix of 75 sensitivity calculations based on a model from a generic safety case was carried out and the results plotted using a spreadsheet in 3 dimensions to enhance understanding of the key controls on the risk from the groundwater pathway [Bailey, 2003].

NRI/RAWRA made deterministic SA calculations within the Czech DGR programme. A large number of calculations have been undertaken with systematically varied parameters in order to investigate the sensitivity of the model. Probabilistic SA has not been performed so far.

Posiva also has undertaken exclusively deterministic SA. In the recent KBS-3V study, a tree-structured organisation of calculation cases was defined. Less likely scenarios are considered sensitivity analysis cases, since they yield information about the system sensitivity against the variation of parameters.

IRSN, as an organisation mainly working for the regulator, follows the recommendations of ASN [ASN, 2008] to define situations that are likely to occur in a normal evolution scenario and then to explore altered evolution cases in order to test the sensitivity.

GRS-Köln as a support organisation of the regulator has used the code SUSA [Kloos, 1999] for probabilistic uncertainty and sensitivity analysis, which, among others, calculates Spearman's rank correlation coefficients. It was used in the framework of the review of the performance assessment for the Konrad LLW/ILW site. The number of runs was limited to 100, which is sufficient to yield a reasonably high confidence level of the tolerance limits in the uncertainty analysis, but is rather low for a SA. So the sensitivity ranking is not considered significant. Another example of SA application was the UTD project [Baltes, 1998], which aimed at exemplary application of safety analysis tools to disposal mines for chemically-toxic waste.

14.6 Developments

Currently, there is some research on probabilistic sensitivity analysis for repository PA models.

Within PAMINA Project, Task 2.1.D dealt with sensitivity analysis, involving GRS, TU Clausthal, JRC, Enresa, NRG and Facilia. Andra performed similar exercises. Task 2.1.D included a comprehensive benchmark exercise with analytical test models and the application of different methods of all types to realistic system models. Useful results have been obtained and a number of specific problems that can arise particularly in repository models have been identified [Becker, 2009].

Some organisations are planning further research in this field.

14.7 Conclusions

There is a wide consensus that sensitivity analysis is an important part of the performance assessment for radioactive waste repositories, and with that, of the safety case. All organisations dealing with performance assessment undertake sensitivity analysis to some extent. The methods applied, however, vary considerably.

Some organisations have only performed deterministic sensitivity analysis. This is a good means to improve the understanding of the system. While it is normally done as a local SA to show directly the influences of the individual parameter to the output, a global SA can also be performed deterministically as performed, e.g., by NDA. This means that two or more values are assigned to each of the relevant input parameters and all possible combinations are calculated, which can, of course, result in a high number of model runs. A typical property of this kind of SA is that parameter distribution functions remain unconsidered.

Probabilistic sensitivity analysis is the approach to global SA that is preferred by most organisations, since it takes account of statistical parameter distributions and keeps the number of runs manageable. Different kinds of methods are available. In most probabilistic

SA studies, correlation or regression methods have been applied. These are suitable for systems with a close-to-linear behaviour, but perform poorly on highly non-linear systems. A rank transformation can be undertaken to transform monotonic to linear relations, which normally improves the qualitative significance of the SA results, at the price of losing their quantitative meaning. Non-parametric statistical tests like the Smirnov test are another means for global probabilistic SA. For all these kinds of methods, different sampling procedures are available. While some organisations have used random sampling (RS), others prefer Latin Hypercube Sampling (LHS).

Some drawbacks of the mentioned methods for probabilistic SA can be avoided by applying variance-based techniques, which are suitable for non-linear and even non-monotonic systems. Some methods (e.g. Sobol, FAST) have been tested with final repository models during recent years by some organisations. Specific problems that are not explicitly addressed in the relevant literature but seem to be essential for repository models have become visible. More research in this area is necessary and planned.

In summary, it can be stated that, although sensitivity analysis is agreed to be necessary, there is no a unique commonly accepted procedure for SA as a part of the safety case. Different organisations follow different valid approaches. The results are successfully used to identify sensitive parameters, but there is no single well-founded and justified general scheme for performing and interpreting SA for repository systems.

14.8 References

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