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

(Contract Number: FP6-036404)

THE TREATMENT OF UNCERTAINTY IN PERFORMANCE ASSESSMENT AND SAFETY CASE DEVELOPMENT: STATE-OF-THE-ART OVERVIEW MILESTONE (N°:M1.2.1)

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Date of issue of this report : **06/08/07**

Start date of project : **01/10/2006** Duration : 36 Months

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
RE	Restricted to a group specified by the partners of the [PAMINA] project	
CO	Confidential, only for partners of the [PAMINA] project	

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 25 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.

The work presented in this report was performed in the scope of RTDC 1.

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

GSL/0546-WP1.2-3
Version 1.0

PAMINA Work Package 1.2

The Treatment of Uncertainty in Performance Assessment and Safety Case Development: State-of-the-Art Overview

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August 2007

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GSL/0546-WP1.2-3
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Report History

This document has been prepared by Galson Sciences Limited (GSL) as part of the European Commission Project PAMINA FP6-036404.

This Version has been revised to take account of comments from Project participants on the Draft dated 20 March 2007, and extensive internal review by GSL.

PAMINA Work Package 1.2 – The Treatment of Uncertainty in Performance Assessment and Safety Case Development: State-of-the-Art Overview				
Version:	Date:	Main Author: D.A. Galson	Reviewed by: M.B. Crawford	Approved by: D.A. Galson
GSL/0546-WP1.2-3 Version 1.0	6 August 2007	Sign …………………… Date ………………………	Sign …………………… Date ……………………	Sign …………………… Date ……………………

Executive Summary

With funding from the European Commission (EC), 26 European organisations are participating in project PAMINA: **P**erformance **A**ssessment (PA) **M**ethodologies **IN** **A**pplication to Guide the Development of the Safety Case. The overall objective is to improve and harmonise PA methodologies and tools for deep geological disposal concepts for long-lived radioactive wastes.

A significant part of the project consists of research on methodologies for the treatment of uncertainty during PA and safety case development, and is being conducted via four interlinked work packages (WPs):

- An initial review task to establish the state-of-the-art with regard to approaches to the treatment of uncertainty in recent safety cases in Europe and worldwide (WP1.2).
- Research focused on key drivers and methodologies for the treatment of uncertainty (WP2.1) – four tasks.
- Research focused on further development and testing of the concepts for treating uncertainty (WP2.2) – five tasks.
- A task pulling together the initial review and the research conducted into a final guidance document on approaches for the treatment of uncertainty during PA and safety case development, and containing a set of state-of-the-art examples for a range of key areas (WP2.3).

This report comprises the initial review (WP1.2) of the treatment of uncertainty in PA and safety case development. Information on treatment of uncertainties was gathered from PAMINA participants and several other organisations using a questionnaire, and via a limited wider review of the literature. This report presents a synthesis of the information gathered, and identifies key discussion points to help focus the implementation of the rest of the PAMINA work programme on the treatment of uncertainty. This document contains several gaps: in particular, topics subject to detailed review as part of the WP2.1 and WP2.2 work programmes were not considered in any detail here to avoid unnecessary duplication of effort. The WP2.3 report will address gaps that are evident in this document.

The questionnaire responses obtained represent 16 disposal programmes in 13 countries, including all of the countries with advanced programmes to implement deep geological disposal, allowing the review to give wide coverage of global activity. Of the responding organisations, four are at the conceptual development or feasibility stage, seven are at the site selection or site characterisation stage, two are at the licensing stage, one is at the construction stage, one is at the operational stage, and one is at the decommissioning/closure stage.

Programme development is accompanied by a wide variation in the development of detailed regulation concerning the treatment of uncertainty for deep geological disposal of radioactive waste.

There is a high level of consensus with respect to the nature of uncertainties in PA and how they should be classified, although this is sometimes masked by variations in terminology and differences in how uncertainties are treated in programmes. A system of classification is set out in this review, with reference to terms describing the nature of uncertainties.

The review identifies how the principal classes of uncertainty are treated in PA programmes, and discusses the division between programmes that primarily use deterministic approaches to PA and those that primarily employ probabilistic approaches. While nearly all programmes have strategies for the treatment of parameter and scenario uncertainties, some do not treat conceptual model uncertainties explicitly.

Questionnaire respondents expressed familiarity with sensitivity analysis techniques, and clearly understand the difference between these and uncertainty analysis. It is less clear how widespread the use of sensitivity analysis is, especially formal mathematical schemes.

Almost no organisations identified uncertainties that may challenge programmes, suggesting a high level of confidence in their ability to site and design deep geological disposal facilities so as to manage uncertainties effectively. However, respondents variously identified the engineered barrier system, the geosphere, the biosphere, and future human intrusion as key sources of uncertainty that require further investigation. The diversity of responses reflects the diversity that exists in programmes in relation to the state of development, regulatory endpoints, engineering design, host rock formation and site characteristics, but may also point to the need for objective methods for determining which part of the PA dominating uncertainties arise from.

Responses on the issue of communicating uncertainties are patchy: some respondents professed to have little experience in this area, while others chose not to answer the question. Some restricted themselves to discussing communication with regulators. Only a few programmes have gone as far as commissioning research into different approaches to communicating uncertainty to a variety of stakeholders.

A significant conclusion from the review is that the WP2.1 and WP2.2 tasks set out in the PAMINA contract Annex 1 are well targeted, and appear to cover nearly all of the topics of greatest interest to respondents. A few possible modifications to the work programme are noted, and these are addressed under individual task discussion points.

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1 Introduction

1.1 Project Context

With funding from the European Commission (EC), 26 European organisations are participating in project PAMINA: **P**erformance **A**ssessment (PA) **M**ethodologies **IN** **A**pplication to Guide the Development of the Safety Case. The overall objective of PAMINA is to improve and harmonise PA methodologies and tools for deep geological disposal concepts for long-lived radioactive wastes.

PAMINA consists of four Research, Technology, and Demonstration Components (RTDCs), and a fifth Component concerned with training, knowledge management and dissemination. The four RTDCs are:

RTDC1: Comprehensive review of methodologies.

RTDC2: Treatment of uncertainty in safety case development.

RTDC3: Other methodological advancements.

RTDC4: Relevance of sophisticated approaches in practical cases.

The treatment and management of uncertainties are integral parts of PA and safety case development because there are significant uncertainties present in long-term assessments of repository safety. For this reason, a large part of PAMINA is concerned with establishing best practice with respect to treating uncertainties, and is being conducted via four interlinked Work Packages (WPs):

- An initial review task to establish the state-of-the-art with regard to approaches to the treatment of uncertainty in recent safety cases in Europe and worldwide (WP1.2) – this document.

- Research focused on key drivers and methodologies for the treatment of uncertainty (WP2.1). This component of RTDC2 comprises four tasks: 2.1.A Regulatory compliance; 2.1.B Communication of uncertainty; 2.1.C Approaches to system PA; 2.1.D Techniques for sensitivity and uncertainty analyses.

- Research focused on further development and testing of the concepts for treating uncertainty (WP2.2). This component of RTDC2 comprises five tasks: 2.2.A Parameter uncertainty; 2.2.B Conceptual model uncertainty; 2.2.C Scenario uncertainty; 2.2.D Spatial variability; 2.2.E Fully probabilistic safety assessment.

- A task pulling together the initial review (this document) and the research conducted into a final guidance document on approaches for the treatment of uncertainty in PA and safety case development, and containing a set of state-of-the-art examples for a range of key areas (WP2.3). The WP1.2 deliverable therefore provides a starting point for development of the WP2.3 deliverable.

PAMINA will run for three years from 1 October 2006 to 30 September 2009. There is a two-year period from April 2007 during which most of the R&D work in RTDC2 will be undertaken.

1.2 Objectives

RTDC1 Work Package 1.2 (WP1.2) has two main objectives:

1. To develop a document that synthesises the state-of-the-art, providing examples on approaches to the treatment of different types of uncertainty at different stages of safety case development and highlighting areas where further development would be helpful (this document).

2. To hold a project workshop to discuss the document, and to discuss and refine the work programme in RTDC2 to support the development of a final guidance document in 2009 on methods and approaches for the treatment of uncertainty. This workshop was held in Brussels on 26-27 March 2007 and is reported elsewhere [Galson Sciences Limited 2007].

This report aims to develop a common understanding and language for different approaches to the treatment of uncertainty in PA, based on current practice in national programmes. At the PAMINA kick-off meeting in October 2006, it was agreed that the WP1.2 review should be conducted based mainly on inputs from project participants. The approach taken has been to gather contributions from PAMINA participants with respect to the treatment of uncertainties in their programmes, and to synthesise these contributions into a report which provides an overview of the state-of-the-art in a non-judgemental manner.

WP1.2 has been separated from the broader review of PA and safety case methodologies in RTDC1 (WP1.1) so that it can be focused particularly on the issue of the treatment of uncertainty, and because the timescale is different from other work in RTDC1, as it is required as an input to RTDC2. However, the general process followed by the review activities in WP1.1 and WP1.2 is similar, and WP1.1 also includes consideration of the issue of uncertainty.

This WP1.2 report is essentially an intermediate product, designed to feed into the workshop held in Brussels in March 2007, where participants used a set of discussion points drawn from the draft report to discuss and develop plans for implementing the RTDC2 work programme. It will eventually feed into the final RTDC2.3 report, which will aim to give a comprehensive review of the subject, including the results of research conducted in RTDC2.

This report contains several gaps; for example, topics subject to detailed review as part of the RTDC2 work programme were not considered in any detail here to avoid unnecessary duplication of effort. The RTDC2.3 report will address gaps that are evident in this document.

The objectives of the workshop held in Brussels on 27-28 March 2007 were:

- To discuss the March 2007 draft of the state-of-the-art report on treatment of uncertainty in PA and safety case development prepared under WP1.2 (this document).

- To discuss the main objectives for RTDC2, and the desired form of the final deliverable from RTDC2.

- To review collectively the specifications for work packages in RTDC2, and ensure that the proposed work is appropriately focused and that the necessary project interactions are identified.

Following detailed workshop sessions, provisional implementation plans for each of the Tasks in RTDC2 were drafted by Task Leaders. These provisional implementation plans are being used to update the RTDC2 work programme, as part of the annual update to be provided to the EC.

1.3 Report Structure

This report is structured as follows:

- Section 2 discusses the approach to the WP1.2 review.

- Section 3 summarises the results of the WP1.2 review.

- Based on the review and consideration of the Technical Annex to the PAMINA contract, Section 4 identifies some questions that can be considered in the conduct of RTDC2 and that were discussed at the March 2007 planning workshop.

- Section 5 contains references.

Responses to the questionnaire circulated as part of the review are included with only relatively minor formatting changes in Appendix A.

2 Approach

2.1 Questionnaire / Scope

As the main basis for conducting the review, a questionnaire was prepared that identified key issues relating to how uncertainties are treated in PA and safety case development for deep geological disposal facilities, as follows:

1. What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?

2. What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?

3. How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.

4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

5. How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.

6. What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?

7. How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.

8. What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.

9. What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.

10. What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?

11. How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.

12. What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.

13. What are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc.?

14. Any other comments?

15. What are the key references that support your response?

In developing the questionnaire, to avoid duplication of effort we did not deal in detail with particular issues that were already planned to be the focus of more detailed reviews in RTDC2. In particular, as part of various tasks within RTDC2, more detailed reviews are foreseen of system approaches to safety assessment (including potential use of "fuzzy" methods, interval mathematics, possibility theory, evidence-based theory, etc.), techniques for sensitivity analyses, methods for expert elicitation, and geostatistical approaches to treating spatial variability.

In addition, the work within PAMINA RTDC2 is focused on the treatment of uncertainty within PA, and not process-level modelling. Furthermore, because of the approach adopted in developing the initial review, this overview report is heavily biased towards summarising information provided in the questionnaire responses. There may therefore be in places an uneven emphasis, reflecting in part the emphases in the questionnaire responses. For example, there is not full coverage of semi-quantitative or qualitative means to address uncertainties (e.g., scenario development methods, confidence building in models, Quality Assurance [QA] measures) – but neither are these issues overlooked.

Finally, the focus of work within PAMINA RTDC2 is on the *treatment of uncertainties* within PA and safety cases. Therefore, issues of *uncertainty management* (e.g., designing out uncertainty, relationship between PA and R&D), though included in the questionnaire and therefore touched upon in this report, do not form part of the R&D work within RTDC2 and are not central to this review.

2.2 Respondents

The questionnaire was distributed to participating organisations in the PAMINA project, and responses were received from the following countries and organisations (organisations are national radioactive waste management companies or support project implementation unless otherwise indicated):

- Belgium: ***ONDRAF/NIRAS*** (National Agency for Radioactive Waste and Enriched Fissile Materials), ***jointly with SCK/CEN*** (Nuclear Research Centre)

  AVN (Association Vincotte Nuclear) (regulator support)

- Czech Republic: ***NRI*** (Nuclear Research Institute)
- France: ***ANDRA*** (National Radioactive Waste Management Agency)

  IRSN (Institute for Radiological Protection and Nuclear Safety) (regulator support)
- Finland ***POSIVA*** (Posiva Company)
- Germany: ***BGR*** (Federal Institute for Geosciences and Natural Resources), ***jointly with DBE*** (DBE Technology), ***and GRS*** (Waste Management and Reactor Safety Company)
- The Netherlands: ***NRG*** (Nuclear Research and Consultancy Group)
- Spain: ***ENRESA*** (National Agency for Radioactive Waste)
- Switzerland: ***Nagra*** (National Co-operative for the Disposal of Radioactive Waste)
- United Kingdom: [1]***Nirex*** (UK Nirex Limited)

In several cases, particular countries are represented by more than one organisation in PAMINA. In such cases, there was a perceived value to be derived from gaining different perspectives from operators and regulators or regulatory support organisations. However, in practice, only two such sets of independent responses were received (from ANDRA and IRSN in France, and from ONDRAF/NIRAS-SCK/CEN and AVN in Belgium).

The response from Germany included information on three different disposal programmes (Morsleben, Konrad, Gorleben).

In addition, the following organisations not participating in PAMINA were invited to make responses to the same questions and to participate in the WP1.2 workshop in Brussels:

- Canada: ***OPG*** (Ontario Power Generation)
- Japan: ***NUMO*** (Nuclear Waste Management Organisation)
- Sweden: ***SKB*** (Swedish Nuclear Fuel and Waste Management Company)

[1] On 1 April 2007, Nirex ceased trading and became the Radioactive Waste Management Directorate (RWMD) of the Nuclear Decommissioning Authority (NDA).

- United States: ***SNL*** (Sandia National Laboratories) – Waste Isolation Pilot Plant (WIPP)

- United States: ***DOE*** (US Department of Energy) – Yucca Mountain Project (YMP)

All five of these organisations provided responses. Note that there are two independent responses from the US because there are two independent deep disposal programmes that have given substantial consideration to the issues being considered in this project.

Taken together, the list of responding organisations ensures that the review gives wide international coverage of current activity.

A draft of the questionnaire was trialled by Nirex and Nagra in November 2006, and experience from that was used to refine the questionnaire. The questionnaire was distributed in late November and responses were received in the period December 2006 – March 2007.

2.3 Form of Responses

The responding organisations provided information in the form they considered most suitable. This generally took the form of written responses to the questions and, in some cases, provision of project documents with specific pointers to where in the documents further information could be found. The full written responses are provided in the Appendix.

Just prior to the launch of PAMINA, some organisations also took part in the questionnaire-based exercise on the INTernational Experience of Safety Cases (INTESC) conducted by the Integration Group for the Safety Case (IGSC) of the OECD Nuclear Energy Agency (NEA). While the OECD/NEA IGSC questionnaire covered some of the same ground, it was broader in content. Some organisations chose to use their responses to the IGSC survey to respond to the questionnaire.

2.4 Other Means of Data Gathering

As well as the responses to the PAMINA WP1.2 questionnaire, a limited amount of additional material was reviewed. This material was obtained from:

- Published literature (conference papers, journal articles) on the treatment of uncertainties in PA.

- Follow-up questions to study participants.

- Comments by participants on the draft version of this report.

2.5 Approach to Synthesis of Information

In synthesising the information obtained, no attempt was made to be comprehensive in summarising all available information. Rather, the aim was for a synthesis of about 40-50 pages that illustrates the types of information in the questionnaire responses and that obtained from the wider review. Where different programmes have adopted different approaches to treatment of uncertainties, the range of the approaches is discussed, and, where possible, some comments provided on the perceived advantages and disadvantages of the various approaches. No attempt has been made to summarise how every programme has addressed every issue in the questionnaire.

Opinions and summaries are those of the authors, and not necessarily those of the participating organisations.

3 Synthesis of Current Practice in Treatment of Uncertainties

The evaluation is reported in sections that correspond directly, and in the same order, to the issues identified in the questionnaire described in Section 2 of this report. The evaluation of responses for questions 4 to 6 was amalgamated, since the questions address different aspects of the same topic. The evaluation of responses to questions 8 and 9 was also amalgamated for the same reason. For ease of reference, at the start of each subsection, we repeat the question(s) being addressed.

3.1 Programme Status in Participating Countries

- *What stage is the radioactive waste disposal programme at in development?*

The state of development of a radioactive waste disposal programme will have a strong influence on the type of PA that is performed in that programme, and consequently how uncertainties in the assessments are treated and presented to stakeholders. The responses from organisations participating in this study demonstrate a wide range of progress towards the implementation of deep geological disposal programmes for long-lived radioactive wastes. Responses cover high-level waste (HLW), spent fuel (SF), intermediate-level waste (ILW), and low-level waste (LLW).

Though there is some variation between responding organisations, the main stages in the development of a typical programme can be described as:

1. Conceptual development, where principal design elements are established.
2. Feasibility studies aimed at establishing the technical viability and inherent safety of designs.
3. Site selection and characterisation.
4. Adoption/licensing by national and local government(s).
5. Construction.
6. Pilot operation/advanced operational testing.
7. Full-scale operation.
8. Decommissioning/closure.

Also, there will be a need for public consultation and regulatory dialogue at several points, possibly throughout all of the stages. Of the responding organisations, currently four projects are at the conceptual development or feasibility stage, seven are at the site selection or characterisation stage, two are at the licensing stage, one is at the construction stage, one is at the operational stage, and one is at the decommissioning/closure stage. A summary of the current status of programmes is given in Table 1 and is described in more detail in Sections 3.1.1 – 3.1.13.

Table 1: Current status of programmes to develop deep geological repositories.

Country	Waste type(s)	Site	Host rock(s) considered	Programme status
Belgium	HLW, SF	None	Clay	Feasibility studies
Canada	ILW, LLW	Bruce site, Kincardine, Ontario	Argillaceous limestone	Site characterisation
Czech Republic	SF	Six potential sites identified	Undecided	Site selection work has been subject to delays
Finland	SF	Olkiluoto, municipality of Eurajoki	Crystalline rock	Detailed characterisation and construction
France	HLW, SF, ILW	Bure	Clay	Feasibility study published – detailed site characterisation underway
Germany	LLW, ILW LLW, ILW HLW	Morsleben Konrad Gorleben	Salt dome Limestone Salt dome	Closure Licensing Site characterisation
Japan	HLW	None	Undecided	Feasibility studies
The Netherlands	HLW	None	Salt dome	Concept development
Spain	SF, ILW	None	Crystalline rock/clay	Feasibility studies
Sweden	SF	Forsmark, Osthammar municipality; Laxemar, Oskarshamn municipality	Crystalline rock	Site selection
Switzerland	SF, HLW, ILW L/ILW	None	Clay preferred Undecided	Feasibility studies completed. Site selection to commence
United Kingdom	HLW, ILW, LLW	None	Undecided	Concept development
United States	TRU (ILW) HLW, SF	WIPP, Carlsbad, NM Yucca Mountain, NV	Bedded salt Tuff	Operation Licensing

3.1.1 Belgium

With the publication of SAFIR 2 (Safety Assessment and Feasibility Interim Report) in 2001, ONDRAF/NIRAS ended the second phase of methodological R&D regarding the deep disposal programme for high-level and long-lived waste [ONDRAF/NIRAS 2001]. Since 2004 the programme has been in the third methodological R&D phase. The current work programme is aimed at establishing if it is feasible, technically and financially, to design, build, operate and close a deep repository on Belgian territory, without prejudging the actual disposal site. The R&D programme is mainly focused on a reference argillaceous host formation (i.e. Boom Clay) and based on *in situ* data acquired in an underground research laboratory located in Mol/Dessel (northeast Belgium).

Neither deep disposal nor argillaceous formations have yet been formally agreed upon or designated by the Belgian Government as the long-term management solution for high-level and long-lived waste. A decision-in-principle to opt for disposal in argillaceous settings will be requested on the basis of a national waste management plan supported by a strategic environmental assessment to be developed by ONDRAF/NIRAS in the next few years (2007-2010). Publication of the Safety and Feasibility Case 1 (SFC 1) by 2013 will lead to a decision to move to site-specific studies. Another issue that needs to be clarified is the make up of the waste, since a decision to impose a moratorium on reprocessing of spent fuel in 1993 (confirmed in 1998), means that reprocessed waste or unprocessed spent fuel or both could require disposal.

AVN is responsible for providing technical support to the Belgian Federal Agency for Nuclear Control (FANC), and reviews the work of ONDRAF/NIRAS.

3.1.2 Canada

The Bruce site in Ontario has been selected for a proposed Deep Geological Repository (DGR) for ILW and LLW [Kempe *et al.* 2007]. The DGR is currently in the Environmental Assessment stage, required to support licensing of the facility, and is awaiting a federal government decision on the process and final guidelines. The first phase of detailed site characterisation is underway. A 2-D seismic survey was carried out in October 2006, and drilling of the first two deep boreholes started at the end of 2006.

3.1.3 Czech Republic

A generic, conceptual design for a deep geological repository for SF at a non-specific site has been completed, including environmental impact assessment and estimates of schedules and budgets. Six potential sites have been evaluated in desktop studies, complemented by airborne geophysical reconnaissance. However, the progression of the programme to geological surveys of sites was interrupted by protests of local inhabitants some three years ago.

The disposal programme in the Czech Republic has been linked to the development of an international regional repository, which will benefit from R&D carried out in the Czech programme.

3.1.4 Finland

The proposal to build a deep geological repository for SF at the Olkiluoto site was approved by national government in 2001. Work on the construction of a test facility (ONKALO), which will later become part of the repository, is already at an advanced stage [Vieno *et al.* 2005] [TKS 2006].

The questionnaire response from POSIVA gives a timeline for the events that have resulted in the current state of the programme. Early site identification studies were carried out in the 1980s. In 1999 POSIVA proposed Olkiluoto in the municipality of Eurajoki as the site for the disposal facility. The Finnish parliament ratified an earlier government policy decision in favour of the project in 2001. Local authorities issued a construction permit for ONKALO in August 2003, with work starting about a year later. Construction of, and installations in, the ONKALO are being carried out in the period 2004-2011, together with characterisation and investigations to support the submission of an application for a licence for full repository construction.

3.1.5 France

ANDRA is responsible for assessing the feasibility of deep geological disposal of ILW and HLW. ANDRA’s remit includes preparation of:

1. A feasibility assessment report on clay formations, namely the Dossier 2005 Argile, based on the work conducted on the site of the Meuse/Haute-Marne Underground Laboratory and in underground laboratories in other countries [ANDRA 2005].

2. A report concerning the advantages of granite rocks based on the available catalogue of French granites and on the investigations carried out by ANDRA under research partnerships with waste management organisations in other countries.

The Dossier 2005 has been approved by the French government, and a phase of detailed site characterisation of clay formations at the Bure site has now commenced.

IRSN is responsible for providing technical support to the French Nuclear Safety Authority (ASN), and reviews the work of ANDRA.

3.1.6 Germany

Aside from the US, Germany is the only country to have experience of operating a deep geological repository for long-lived wastes. The Bartensleben rock-salt mine near Morsleben in Saxony-Anhalt operated between 1981 and 1998. Approval is currently being sought for backfilling and sealing this facility.

For radioactive waste with negligible heat generation (causing a temperature increase of less than 3°C in the host rock), the Konrad repository is licensed.

The Gorleben salt dome has been investigated as a potential repository site for all types of radioactive waste, including HLW. The detailed site characterisation was interrupted in 2000 for political reasons. A detailed probabilistic assessment of a repository for HLW has been conducted [Buhmann *et al.* 1991].

In 2002 recommendations were made at federal level on a procedure for selecting candidate sites for deep geological repositories, with the start of repository operations scheduled for 2030.

3.1.7 Japan

The Japanese programme for geological disposal of HLW began an implementation phase in 2000, and NUMO was subsequently established as the implementer. This was preceded by generic feasibility studies [JNC 2000].

The siting process [NUMO 2004] will consist of three steps. First, Preliminary Investigation Areas (PIAs) for potential candidate sites are nominated based on site-specific literature surveys focusing on long-term stability of the geological environment. Second, Detailed Investigation Areas (DIAs) for candidate sites are selected from PIAs following surface-based investigations, including boreholes, carried out to evaluate the characteristics of the geological environment. Third, detailed site characterisation, including investigations using underground research facilities, leads to selection of the site for repository construction. According to the current schedule, the repository will be in operation from the mid-2030s.

NUMO announced the start of open solicitation of volunteer municipalities for PIAs with publication of an information package in December 2002. So far only one application has been received: from Toyo town in Kochi prefecture, effective 25 January 2007 – but is has since been withdrawn. NUMO is continuing to call for other municipalities to apply as volunteer areas.

3.1.8 Netherlands

The programme in the Netherlands is currently at the concept development stage. The relatively small quantities of SF produced in the country, with only one operating nuclear power plant (Borssele), along with the recent commissioning of an interim storage facility in 2003, means that there is little demand for the construction of a deep geological repository in the immediate future.

3.1.9 Spain

The Spanish programme for deep geological disposal is currently at the stage of generic feasibility studies. There is no immediate prospect of moving onto the next phase of development - identification of candidate sites and site-specific feasibility studies. A policy plan for SF and HLW exists in the form of the 6th General Radioactive Waste Plan [MITC 2005], which states that the strategy for the medium term is to focus on provision of dry storage at the surface, in order to allow sufficient time for decisions on long-term waste management to be made.

3.1.10 Sweden

SKB has been investigating the feasibility of geologic disposal of SF since the late 1970s. The KBS-3 repository concept (copper canisters, bentonite buffer, crystalline host rock) was formally adopted by SKB in the 1990s. In 2001 the Swedish government endorsed a plan to carry out site-specific studies at three sites, using the KBS-3 repository concept as the basis for the studies. At two of these sites, Forsmark and Laxemar, local authorities granted permission to embark upon programmes of site characterisation.

SKB published its interim SR-Can safety assessment in late 2006 [SKB 2006a], and publication of the SR-Site assessment is planned for 2008. This document will identify the preferred site for repository construction, and will be followed by licensing and, if approved, repository construction. Full-scale operation of the repository and waste encapsulation plant is scheduled for ~2015.

3.1.11 Switzerland

Project Opalinus Clay [Nagra 2002a, 2002b], a feasibility study for a repository for SF, HLW and ILW based on detailed field investigations, was approved by the Swiss Government in June 2006, following its submission by Nagra in 2002 and subsequent review and consultation processes. A site selection process for deep geological repositories for all radioactive wastes (SF, HLW, ILW, L/ILW) is currently being defined by the Government.

Plans to build a repository for L/ILW at Wellenberg, Canton of Nidwalden, had to be abandoned after the population of the Canton of Nidwalden rejected the plans for the proposed underground investigation tunnel in 2002. The site selection process for the L/ILW repository will now proceed in parallel to that for the SF/HLW/ILW repository.

3.1.12 United Kingdom

The programme for the development of an ILW disposal facility in the UK returned to the conceptual development stage upon rejection of proposals by government in 1997 to build an underground test facility at Sellafield, Cumbria [Nirex 2003, 2005]. However, following a recent consultation and review of generic long-term solutions for disposal of radioactive waste by the Committee on Radioactive Waste Management (CoRWM) [CoRWM 2006], in 2006 the UK government endorsed the principle of developing deep geological repositories all long-lived wastes. The programme is still in the detailed concept development and assessment stage, though site selection may start within the next few years.

3.1.13 United States

In 1979, the US government authorised construction of the WIPP, a deep geological repository in a bedded salt formation near Carlsbad, NM, for the disposal of transuranic (TRU) wastes from US defence programmes. The WIPP was certified by the US Environmental Protection Agency (EPA) in 1998, and the first waste shipment was received in 1999. The WIPP is expected to operate for ~35 years, during which time it will receive ~19,500 shipments of waste.

A national repository for commercially produced SF and defence HLW has been under investigation by the DOE since passage of the Nuclear Waste Policy Act of 1982, which placed responsibility for final disposal of such wastes with the federal government. A welded tuff formation in the unsaturated zone beneath Yucca Mountain (Nevada) has been the focus of site characterisation activities since 1987. In 2002, the Congress and President approved Yucca Mountain as the location for the nation's SF and HLW repository. This allowed the DOE to prepare a license application to request a construction authorisation from the US Nuclear Regulatory Commission (NRC). It was originally hoped that the repository would be in operation by 2010; however, timetables have slipped, in part due to significant opposition from the State of Nevada and other stakeholders. The Yucca Mountain Project is now due to submit a license application in 2008 to the NRC.

3.2 Regulatory Requirements and the Treatment of Uncertainty

- *What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?*

The uncertainties present in PAs and safety cases for deep geological repositories present problems for any system of regulation that may be used to license such facilities. Lack of consideration or mismanagement of uncertainties by repository developers can seriously impact regulatory compliance. The regulatory regimes operating in some of the participating countries therefore contain specific requirements for the treatment of uncertainties in PA and in safety cases.

We summarise here the status of regulation specific to deep geological repositories (Section 3.2.1), discuss primary receptors considered in such regulation (Section 3.2.2), and – based on the review – conclude with general observations on how uncertainty can be considered in regulation (Section 3.2.3).

3.2.1 Status of regulation specific to deep geological disposal

International Context

A European Pilot Study on the Regulatory Review of the Safety Case for Geological Disposal of Radioactive Waste has been established on the basis of agreement between several European regulators. The Pilot Study seeks to consider jointly how issues raised in implementing deep geological disposal facilities can be addressed in regulation. A case study considering the treatment of uncertainties in safety cases for geological repositories has recently been published, based on co-operative work between regulators in Belgium, France, Germany, Switzerland, and the UK [Vigfusson *et al.* 2007].

In addition, the International Atomic Energy Agency (IAEA) is taking an increasing interest in the establishment of safety requirements and guidance directed towards the disposal of radioactive wastes. For example, the IAEA has recently published Safety Requirements on geological disposal of radioactive waste [IAEA 2006].

Finally, regulatory development is also being assisted by the OECD/NEA, which, among other things, sponsored a workshop in Stockholm in 2004 [OECD/NEA 2004] that considered issues of uncertainty and risk in regulation.

National Developments

There is wide variation in the development of regulation covering the treatment of uncertainty for deep geological disposal of radioactive wastes, with the more advanced countries having developed regulations and some countries that are still at the concept development/feasibility stage having no specific regulation yet. We provide below several examples, first of more detailed regulation, followed by several examples of programmes that are at a more variable level of regulatory development.

In the UK, 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 (the Guidance on Requirements for Authorisation, the GRA) [Environment Agency *et al.* 1997]. The GRA includes four principles and eleven requirements covering all aspects of the design, construction, operation and closure of a radioactive waste repository. In particular, for the period after the withdrawal of institutional controls, the GRA states that: "*…the assessed radiological risk from the facility to a representative member of the potentially exposed group at greatest risk should be consistent with the risk target of* 10^{-6} *per year ...*" The term potentially exposed group is used where the exposure is not certain to occur.

The GRA also specifies that: "*The developer should … present the range of possible doses which each potentially exposed group may receive, together with the probability that the group receives any given dose.*" The GRA notes that "*…sufficient assurance of safety is likely to be achieved only through considerations rather broader than purely the numerical evaluation or risk…*" and asks for the use of *"…multiple and complementary lines of reasoning"*. The GRA asks that the information provided by the developer include, 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…*".

In Finland, where the programme has advanced to the repository construction stage, specific regulatory guidance was given as part of the government decision in favour of the POSIVA programme in 1999. This guidance establishes that a safety assessment shall include uncertainty and sensitivity analyses and complementary discussions of such phenomena and events that cannot be assessed quantitatively. The regulatory approach in Finland also endorses the idea of using conservative modelling assumptions so as to provide a high level of confidence that potential future radiological exposures are over-estimated.

In Switzerland, the R-21 guidelines for the geologic disposal of radioactive waste [HSK & KSA 1993] contain three protection principles: a limitation on annual individual dose of 0.1 mSv/y; a limitation on individual risk of 10^{-6} /y; and a requirement that the repository can be sealed within a few years and that after sealing no further measures shall be necessary to ensure safety. In addition, the Nagra response to the questionnaire points out that:

"*No time cut-off is specified for post-closure assessments. HSK/KSA suggest that '...dose and risk calculations should be carried out for the distant future, at least for the maximum potential consequences from the repository...'. It is however recognised that, in view of uncertainties, dose calculations for the distant future are to be interpreted as indicators, and should be based on the use of ' ... reference biospheres and a potentially effected population group with realistic, from a current point of view, living habits …'*

"Regarding the treatment of uncertainty in models and datasets, R-21 states:

> *'When calculating dose or risk, the applicant has to give the possible ranges of variation of the relevant data. He also has to give the range of variation in the results following from these data. Conservative assumptions are to be made, where uncertainties remain. Uncertainties which are due to incomplete knowledge of the properties of the repository system and to incomplete understanding or simplified modelling of release and migration mechanisms have also to be estimated.'"*

In the US, specific and comprehensive regulation has been implemented for the licensing of the WIPP [EPA 1993, 1996a, 1996b]. These regulations provide the developer a detailed, prescriptive path for the conduct 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, the WIPP must comply with individual and groundwater protection standards.

The EPA and the NRC are currently developing the standards that will apply to the disposal of HLW and SF in the potential repository at Yucca Mountain (proposed 40 CFR Part 197 and 10 CFR Part 63). These standards differ from those that apply to the WIPP in that the main assessment endpoint is 'critical group' dose to an individual member of the public, rather than cumulative release of radionuclides.

The DOE-YMP response to this question contains substantial detail on the likely NRC regulation:

"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)'*

"The regulatory guidelines also require a demonstration of reasonable expectation in the compliance calculations vis-à-vis the following acceptance criteria:

- *Does not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence;*

- *Focuses performance assessments and analyses on the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values.*

"The EPA has recently proposed public health and safety standards in proposed 40 CFR Part 197 (64 FR 46976), with which the potential repository at Yucca Mountain must comply. The EPA has also specified the application of a probabilistic framework where uncertainties associated with scenarios, models, and parameters are explicitly incorporated into the performance assessments for demonstration of compliance. The regulation specified by the NRC in proposed 10 CFR Part 63 (64 FR 8640) is intended to implement EPA's standards and be consistent with the EPA requirements".

In Canada, the Canadian Nuclear Safety Council (CNSC) recently published non-mandatory regulatory guide G-320 on "Assessing Long Term Safety of Radioactive Waste Management" [CNSC 2006], which addresses issues relevant to deep geological disposal facilities, including recommended assessment methods and the treatment of uncertainties. A scoping document sets out similar PA methods for the site-specific Environmental Assessment that the Canadian programme is preparing for, and will be required for licensing of the proposed disposal facility. High-level policy with regard to geological disposal is contained in the CNSC policy document P-290 [CNSC 2004].

G320 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:*
> 1. *Scoping assessments to illustrate the factors that are important to long term safety;*
> 2. *Bounding assessments to show the limits of potential impact;*
> 3. *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*
> 4. *Deterministic or probabilistic calculations, appropriate for the purpose of the assessment, to reflect data uncertainty.*
>
> (Section 5.2 of G-320)
>
> *'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.* (Section 5.2.3 of G-320)
>
> *'The need to evaluate the uncertainty in the assessment model through deterministic sensitivity analyses or through probabilistic calculations is determined by the level of confidence needed in the model results. The acceptable level of confidence is governed by the purpose of the assessment, the safety factor built into the acceptance criteria for*

> *safety indicators, and the importance of the assessment model results to the safety case…* (Section 7.6.3 of G-320)
>
> *'…Model evaluation should include sensitivity analyses to show whether the model output responds as expected to variations in the model input parameter values. Model evaluation should also include uncertainty and importance analyses to show which parameters control the variability in model output. These analyses should demonstrate how well the model replicates what is known and understood about the processes and mechanisms being simulated…* (Section 7.6.3 of G-320)
>
> *'…Neither sensitivity studies nor uncertainty analyses of deterministic or probabilistic models can inherently account for uncertainties in the underlying conceptual model, or uncertainties resulting from limitations of the mathematical model used to describe the processes. Investigation of such uncertainties would require the use of different mathematical and computer models based on alternate conceptual models. Confidence in the assessment model can be enhanced through a number of activities, including (without being limited to):*
> 1. *Performing independent predictions using entirely different assessment strategies and computing tools;*
> 2. *Demonstrating consistency between the results of the long term assessment model and complementary scoping and bounding assessments;*
> 3. *Applying the assessment model to an analog of the waste management system;*
> 4. *Performing model comparison studies of benchmark problems;*
> 5. *Scientific peer review by publication in open literature; and*
> 6. *Widespread use by the scientific and technical community.'* (Section 7.6.3 of G-320)

In France, regulatory advice regarding deep geological disposal is contained in Basic Safety Rule III.2.f. [DSIN 1991]. The philosophy that informs the regulatory regime has its source in engineering disciplines where there are highly developed techniques for dealing with 'risk'. In the 'Dossier 2001' [ANDRA 2003], a scheme was proposed by ANDRA for treating uncertainties through the safety case by referring to the notions of risk analysis, known as 'qualitative safety analysis' (AQS).

In Belgium, while no specific regulation currently exists for deep geological disposal, AVN has produced a draft document providing guidance on siting a geological disposal facility in argillaceous sedimentary formations [AVN 2005]. The document contains fundamental requirements to be fulfilled by the host formation and provides guidance on the role to be fulfilled by the environment of the disposal system.

The programme in Spain is at the stage of general feasibility studies, and so far there has been only limited regulatory development for geological disposal. Currently the only regulatory criteria established are that the individual equivalent effective dose does not exceed 10^{-4} Sv/y, or that the individual annual risk does not exceed 10^{-6}. There are no specific requirements on the treatment of uncertainty.

In Japan, the Nuclear Safety Commission (NSC) and the Nuclear Industrial Safety Agency (NISA) have begun the process of formulating regulations [NSC 2004, NISA 2003].

3.2.2 Primary performance measures used in regulation

The majority of regulatory regimes adopt dose to an individual member of a 'critical group' or a 'potentially exposed group' as a primary quantity for assessing the long-term consequences of a deep geological disposal facility, most commonly through the imposition of an annual exposure limit on effective dose from all sources, and dose constraints that apply to individual sources. As doses are being calculated for hypothetical individuals in the far future, it is commonly recognised that the calculations can ever only be illustrative in nature.

The dose limit for members of the public from all practices is usually set to the International Commission on Radiological Protection (ICRP)-recommended level of 1 mSv/yr, and the source-related constraint (e.g. for a single repository) is typically in the range 0.1 to 0.5 mSv/y. The use of a 'critical group' dose concept takes account of variability in a population with regard to habits that determine exposure, for example diet and occupancy rates within buildings or at defined locations, and enables illustrative calculations to be made of potential doses received by hypothetical individuals that could comprise the most exposed part of a future population.

Annual 'risk' to an individual member of a potentially exposed group is also frequently used as a primary regulatory quantity. The use of risk has the advantage that it allows the probability of occurrence of unlikely events and processes to be explicitly accounted for in evaluating compliance. On the other hand, in practice it can prove extremely difficult to estimate probabilities of occurrence for unlikely events and processes. Like calculated individual doses, calculated individual risks in the far future are also only ever illustrative.

The quantity of 'risk' has a closer relationship to potential health impact than dose, in the sense that dose limits are derived from a back calculation from an assumed tolerable level of risk (typically that which would be considered negligible by most individuals). Therefore, the use of individual risk as a regulatory performance measure avoids making the regulations themselves dependent on the complex relationship between radiation dose and health impacts, which in the past has been subject to revision through changes in scientific advice. However, it places a burden on the safety case developer to remain aware of any changes in the dose-to-risk conversion factor and to calculate risks accordingly.

A different approach is used in regulations for the WIPP, where the fundamental regulated quantity for long-term PA is the cumulative amount of radionuclides that can be released to the accessible environment over 10,000 years. Limits on cumulative releases were derived by the regulator based on back calculation from dose for a range of conceptual HLW repositories. The regulations require these releases to be expressed in the form of complementary cumulative distribution functions (CCDFs) that represent the probability of exceeding various levels of cumulative release. This is akin to the total activity limits placed on radioactive discharges from conventional nuclear sites, but with a modification to deal with the extended time span of the release. The problem here is in then understanding the actual relationship between the cumulative releases and radiological consequences for a specific site.

Because of the illustrative nature of dose and risk calculations, some countries have also considered establishing alternative primary performance measures. For example, in the ongoing discussions about the development of safety requirements in Germany, an approach based on demonstration of the confinement of radionuclides has been proposed. Most of the proposed indicators - namely the fraction of released amount of substance, the concentration of released U and Th, the contribution of released radionuclides to power density in groundwater, and the contribution to radiotoxicity flux in groundwater - are located in the vicinity of the so-called "isolating rock zone", rather than in the accessible environment. The function of the isolating rock zone is, together with the engineered barriers, to ensure the confinement of the waste for a defined isolation period during normal evolution of the repository. As far as possible, indicators are relied upon that can be calculated based on modelling of system components that are relevant for safety and the evolution of which can be forecast over the assessment timeframe, rather than on largely hypothetical considerations of biosphere evolution and possible exposures to individual members of future human populations.

Following development of a conceptual dosimetric framework for wildlife and the environment by ICRP [ICRP 2003], and EC-funded research in this area [Larsson 2004], it is anticipated that dose to non-human biota will be included as a performance measure in some regulatory regimes. Recently formulated guidance in Canada [CNSC 2006] already incorporates such provisions.

Many of the issues discussed here are also reviewed in the paper given by Wilmot to the 2004 OECD/NEA meeting in Stockholm [Wilmot 2004].

3.2.3 Regulatory requirements to treat uncertainties in PA

Regulatory requirements on the treatment of uncertainties in PAs vary from detailed mandatory requirements in the case of, say, the WIPP project, with the use of a prescribed methodology, to none at all in some programmes still at the concept development stage. In all cases where programmes have developed past the initial stages, regulators accept the need to address uncertainties inherent in PA for deep geological disposal.

Examination of regulatory approaches towards the treatment of uncertainties in PA delineates the following, potentially overlapping options:

1. Mandatory, prescribed methods for the treatment of uncertainty.

2. Detailed regulatory guidance or "expectations" on treatment of uncertainty; objectives defined only.

3. No particular national guidance yet defined for geological disposal; direct use of international (i.e., IAEA, ICRP) guidance on disposal or reliance on pre-existing regulatory framework.

To a greater or lesser extent, in adopting one or more of these approaches regulators share the burden of making the safety case for geologic disposal and deciding on PA assumptions and requirements, with approach (1) placing the greatest burden on the regulator for pre-licensing consideration of uncertainty treatment and the safety case. The advantages of approach (1) are consistency in the standard of assessments, at least in presentational terms, and the clearer framework for planning and dialogue by developers and regulators. The main drawback to adopting prescriptive regulation is that it could narrow the range of likely results and the way in which they are presented, and may bias the outcome of assessments through not considering local factors and excluding the use of better methods.

The regulatory approach adopted for the WIPP project can broadly be placed in category (1). Since the WIPP is unique in being licensed and operational, the following details provided by the SNL-WIPP response to the questionnaire are of interest:

"The WIPP-specific Certification Criteria of 40 Code of Federal Regulations (CFR) 194 require that a probabilistic risk assessment be performed and dictates how the "Performance Assessment" (PA) must be conducted. These criteria also detail how uncertainty must be treated. The following requirements pertain to system parameters:

- *Probability distributions for uncertain disposal system parameters must be developed.*

- *The entire range of the probability distributions must be sampled.*

- *It is assumed that future drilling practices and technology will remain consistent with current practices.*

"With regard to repository performance, the following principal regulations exist:

- *Features, Events, and Processes (FEPs) that have less than a 1 in 10,000 chance of occurring during 10,000 years do not need to be considered in performance assessment. Probabilities this small would tend to be limited to phenomena such as the appearance of new volcanoes outside of known areas of volcanic activity, and the EPA saw no benefit to public health or the environment from trying to regulate the consequences of such highly unlikely events.*

- *The results of the performance assessments must be assembled into complementary, cumulative distribution functions (CCDFs) that represent the probability of exceeding various levels of cumulative release.*

- *The number of CCDFs generated must be large enough such that the maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least 0.95 probability.*

- *It must be demonstrated that there is at least 95 % level of confidence that the mean CCDF meets containment requirements.*

"The containment requirements of 40 CFR 191.13 specify a 10,000 year performance period. A period of 10,000 years was considered long enough to distinguish geologic repositories with relatively good capabilities to isolate wastes from those with relatively poor capabilities. This period was considered short enough so that major geologic changes would be unlikely and repository performance might be reasonably projected."

The WIPP approach is of interest because it represents a highly developed example of its kind, and practical experience has been gathered of its use - however, there is no international consensus that it is best practice. Indeed, more recent developments in the United States appear to move away from it.

The regulatory approach to treatment of uncertainties that many countries are taking is (2), through the publication of non-binding guidance 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 adopted in Canada and has been discussed in the European Pilot Project [Vigfusson *et al.* 2007].

Approach (3) is not foreseen anywhere for licensing of deep repositories but, where the implementation of disposal projects is still some way off, specific national regulations may not yet have been developed. The lack of disposal regulation does not stop projects in these countries from undertaking feasibility studies, PA, safety case, and even siting work. This is so for two reasons. First, an increasing number of international requirements and guidance documents specific to geological disposal has become available in the last 10 or so years [e.g., IAEA 2006]. In addition, there is a highly evolved system of regulation and guidance for radioactive discharges at international and national level that takes into account the uncertainties present in radiological assessments; applying these regulations in a non-prescriptive way provides a framework for considering releases from a deep geological disposal facility as well at the feasibility stage.

Approach (3) may also be useful for countries that produce little of their own radioactive waste, where there may be limited expertise and infrastructure for radioactive waste management, but where there is still a need to provide a national site for a deep geological repository.

3.3 Types of Uncertainties Considered in PA

- *How have the main types of uncertainties been classified for consideration?*

There is a high level of consensus on both how uncertainties considered in PA should be *classified* and the *nature* of uncertainties, although this is masked by variations in terminology and differences in how uncertainties are treated in programmes.

The majority of respondents provided a consistent conceptual classification of the uncertainties considered in PA in the following way:

1. 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. This type of uncertainty is often called "model" uncertainty. It includes uncertainties that arise from the modelling process, including assumptions associated with the reduction of complex "process" models to simplified or stylised conceptual models for PA purposes, assumptions associated with the representation of conceptual models in mathematical form, and the inexact implementation of mathematical models in numerical form and in computer codes.

2. Uncertainties associated with the values of the parameters that are used in the implemented models. They are variously termed "parameter", or "data" uncertainties. They arise mainly from the following sources:

   (a) The parameter values cannot be determined exactly because:

      i. The parameter values cannot be measured accurately;

      ii. The model requires parameter values applicable to scales for which values are not measurable, and the values have thus to be transferred, averaged or "upscaled" from values available for a different measurement scale (e.g., the use of laboratory-derived measurements to estimate *in situ* values); and/or

      iii. The parameter is a simplified representation of a more complex phenomenon, which is not fully understood and/or characterised, or is too difficult to model within a PA (e.g., bulk sorption is a simplified representation of many processes).

   (b) The models use single (or spatially averaged) values for parameters, derived from measurements at discrete locations, whereas in reality there is continuous variation in parameter values over space - as well as over time (variability).

3. 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.

All three *classes* of uncertainty are related to each other, and particular uncertainties can be handled in different ways, such that they might be dealt with in one class or another for any single iteration of a PA/safety case, depending on programmatic decisions (e.g., on how to best communicate results) and practical limitations (e.g., on funding or timescales). For example, uncertainties associated with future climate change are dealt with in some PAs as a “scenario” uncertainty, via the establishment of separate scenarios for different possible climate futures, and in other PAs as a “parameter” uncertainty within a single scenario, via theoretical consideration of possible climate variability and the establishment of appropriate probability distribution functions (PDFs) for groundwater flow models and radionuclide transfer factors in biosphere models.

The *classification* system for uncertainties given above essentially arises from the way PA is implemented, and says little about the *nature* of the uncertainties. With respect to *nature*, a useful distinction can be made between *epistemic* and *aleatory* uncertainties. *Epistemic* uncertainties are knowledge-based and, therefore, reducible by nature. *Aleatory* uncertainties, on the other hand, are random in nature and are irreducible.

All three *classes* of uncertainty contain elements that are *epistemic* and *aleatory*, although it may be generally true that “scenario” uncertainties contain a larger element of *aleatory* uncertainty than the other two groups. To take an example, typically “parameter” uncertainties may arise for the following reasons, as noted above:

- The parameter values have not been determined exactly. This type of uncertainty is largely *epistemic* in quality, and can be reduced with further effort.

- The models use single values for parameters, whereas in reality there is variation in parameter values over space and time. This type of uncertainty is partly *aleatory* in quality and cannot be reduced by further effort.

This system of describing the *classification* and *nature* of uncertainties is summarised in Figure 1.

An issue of interest is how to best explain and present the increasing level of uncertainty in a PA with time. Some assessments are now being conducted and presented using a “timeframes” approach, whereby safety functions are assigned to different parts (barriers) of the disposal system, and these barriers are expected to provide a certain level of performance over a certain period.

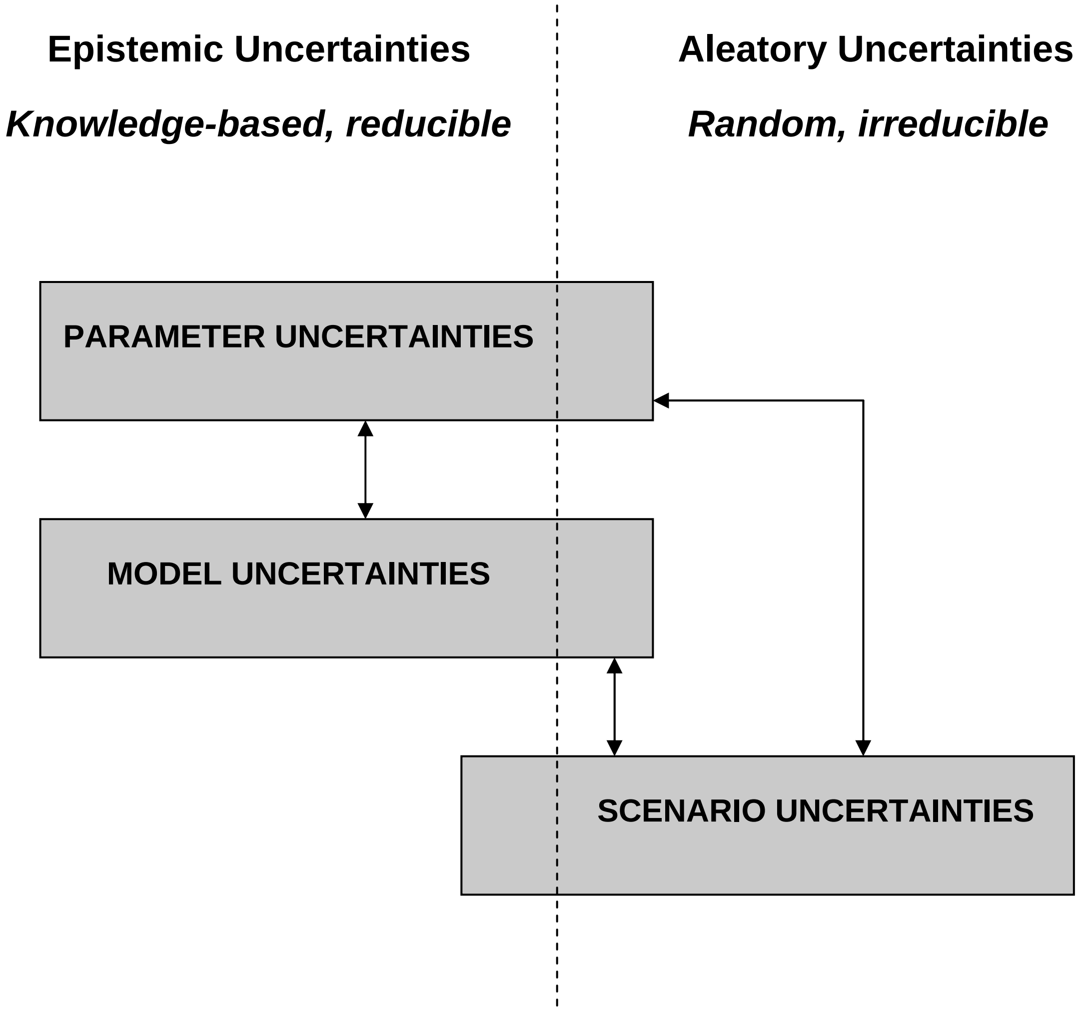

Fig 1. *Classification* and *nature* of uncertainties in PAs.

3.3.1 Example of different types of uncertainties

The following idealised example illustrates the three *classes* of uncertainty that occur in PA. Consider a radionuclide flux from a repository borne by groundwater through fractured rock, such as would occur if a repository were situated in crystalline bedrock. PA receptors are situated at ground level above the repository, and a very simple PA model represents transport of radionuclides by vertical advection through a homogenous rock layer to a well from which water is drunk by a member of the public. Radionuclide transport from the repository to the well is described as a single, fixed, upward flow rate for groundwater f_1 ($y^{-1}m^{-2}$) and a single, fixed, downward flow rate for infiltration f_2 ($y^{-1}m^{-2}$). Retardation of radionuclide species is modelled using a bulk sorption coefficient, K_d, for each radionuclide species.

Considering the parameter K_d, there are uncertainties that arise from:

1. Representation of the fractured multilayer rock medium by a homogenous, single layer.

2. Representation of complex, non-linear, reactive chemical processes, which may not be fully understood, by the simple linear sorption model represented by the bulk sorption coefficient K_d.

3. Assumptions about the chemical forms of the radionuclide species.

4. Time-dependent changes that affect groundwater chemistry.

In this case, given the choice of K_d to represent uncertainty, these could all be considered examples of "parameter" uncertainty. The difficulties in quantifying these uncertainties in terms of a parameter range are compounded by the fact that, as a parameter in a highly stylised, simplified model, K_d cannot be directly mapped to a single measurable quantity.

The relationship between "parameter" and "model" uncertainties is illustrated if the very simple model is replaced by a more complex model that simulates transport through a series of rock fractures. In this model, sorption occurs at the fracture surfaces, leading to a change in the way that sorption is specified: the K_d parameter, if retained, would have a modified range in the new formulation.

The characteristics of "model" uncertainties are illustrated by representing the problem with increasing levels of detail such as fracture structure and connectivity, and alternative formulations for describing physical processes such as flow through fractures, diffusion and reactive chemistry. For the purpose of assessing the potential impact of "model" uncertainties, several stylised concepts may be developed that represent the range of model conceptualisations in terms of PA outcomes.

"Scenario" uncertainties are illustrated by considering the occurrence of events or gradual changes over time that may significantly influence outcomes at the receptor level. A large number of these can be identified, but two simple cases would be:

1. Changing climate may significantly change groundwater flow pathways and properties over time, necessitating fundamental changes to the groundwater flow model or the introduction of new flow parameters.

2. Future human activity, from say drilling into the host rock, may accelerate transport of the radionuclides to surface layers, requiring specific models and new parameters to be introduced.

3.4 Dealing with Uncertainty in the Quantitative PA

This section relates to the treatment of uncertainties within the quantitative PA. It synthesises responses to questions 4-6 in the questionnaire, which cover different aspects of essentially the same topic:

- *How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case?*

- *How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties?*

- *What approach to system PA is preferred / appropriate and why?*

A large part of the treatment of uncertainties within a safety case is conducted outside the quantitative PA, and it can be argued that these measures ultimately contribute as much to the robustness of the safety case as the quantitative PA. Qualitative treatment of uncertainties is addressed in Section 3.6.

3.4.1 Parameter uncertainty

Uncertainties associated with model parameters can be treated conveniently within most computational schemes. All of the programmes included in this study contain measures to treat parameter uncertainties in the formal quantitative PA. Common approaches to treating parameter uncertainty are:

1. Setting PDFs for parameters, which are sampled during the course of a probabilistic assessment.

2. Repeat deterministic calculations where individual parameter values are varied across a range of likely or possible values, including deterministic calculations using values representing the best understanding available ("best estimate") in order to better understand the system, e.g. with regard to sensitivities.

3. Deterministic calculations where deliberately pessimistic values of parameters are taken, producing a "conservative" estimate of the value of receptor quantities in order to demonstrate compliance with limits.

Surveying the practices across the participating countries, a simplistic summary of the current situation might place programmes in two camps: those that rely primarily on the probabilistic approach described in (1) and those that primarily use deterministic approaches (2) and (3). In the first camp, programmes in the US are notable champions. However, this is, increasingly, an over-simplified summary.

Several respondents stated that while a probabilistic approach is the preferred one, it is supplemented by deterministic calculations (e.g., Germany, the Netherlands, Spain, and the UK). The reasons most commonly given for this preference is the ease with which probabilistic calculations are done and completeness in terms of describing the whole system from source to receptor. The programme in Sweden uses probabilistic calculations to supplement deterministic ones, mostly for the more complete treatment of parameter uncertainty that the probabilistic calculations afford and because of the new risk-based regulation in Sweden. Programmes in Belgium, Finland, France, Japan and Switzerland are in the camp that favours largely deterministic approaches, but probabilistic approaches have been or are being considered in these countries to supplement the deterministic calculations. There is a view that a deterministic approach has advantages where there are very large uncertainties in the PA, and where the use of deterministic approaches allows a more transparent treatment of uncertainty (e.g., AVN, Belgium). As discussed in Section 3.2, regulation can play an important role in determining which approaches to PA are adopted for compliance calculations.

3.4.1.1 Probabilistic approach to treating parameter uncertainties

Whether a probabilistic approach is used for a small component of a PA, or the whole system, many of the issues with respect to treating uncertainty are common. The total system approach is supported by the increasing availability of user-friendly software (e.g., GoldSim) that allows near field, far field and biosphere to be modelled in a single implementation of the whole system, and perform many calculations in a short time. The greater part of the effort is taken up with determining PDFs for uncertain parameters. Performing the calculations themselves is relatively quick with modern software and is becoming quicker still through the continuing increase in computing power.

The following issues are associated with this approach:

- It is not necessarily straightforward to derive meaningful PDFs from available data for uncertain parameters, and inappropriate choices could bias the results.

- Possible couplings (correlations) between parameter values need to be identified and incorporated into sampling schemes.

- Care is needed to ensure sufficient sampling of parameter space for PDFs that have long tails.

- Care is needed to identify and avoid “risk dilution”, whereby an increase in parameter uncertainty results in a decrease in calculated mean annual individual dose or risk. This effect can be identified by comparing the peak of the calculated mean (dose or risk) with the mean of the individual peaks from each model run.

- There may be a lack of transparency in implementing a single model that aggregates all outcomes.

At worst, the probabilistic approach can foster a false sense of confidence that all uncertainties have been included in the assessment, and may lead to focus excessively on total system inputs and outputs and so detract from understanding the underpinning causes of the behaviour of the repository system.

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.

In Canada, the safety case for the proposed deep geologic repository for L/ILW at the Bruce site, Ontario will use both probabilistic and deterministic methods for treating parameter uncertainties [Kempe *et al.* 2007].

Work has been conducted for the Canadian SF disposal programme on identifying key parameters and defining the shapes of PDFs that can be used in probabilistic assessment, and a formal method has been developed for performing sensitivity studies using Iterated Fractional Factorial Design (IFFD) [Melnyk *et al.* 2006]. This showed that the choice of PDF shapes can have a significant impact on calculated assessment endpoints; the mean calculated dose rate is a factor of ten higher if peaked PDFs are replaced with level distributions over the same ranges.

The importance of finding PDF shapes that are appropriate to the level of knowledge for parameters is widely appreciated, and has been noted in the responses from several respondents. For example, the response from ONDRAF/NIRAS and SCK/CEN (Belgium) indicates that, owing to a lack of sufficient empirical data, they have described most parameter uncertainties using a log-uniform distribution, for which a best estimate value and an uncertainty factor are estimated.

In Sweden, strategies for treating parameter uncertainties are set out in the Data Report for SR-Can [SKB 2006b]. For each of 21 groups of parameters associated with separate parts of the PA, such as ‘Thermal Properties’ or ‘Fracture Data’, a protocol is followed describing:

1. Modelling in SR-Can.
2. Impact on assessment results.
3. Source of information.
4. Conditions for which data are supplied.
5. Conceptual uncertainties.
6. Data uncertainties, spatial and temporal variation.
7. Correlations.
8. Quantification.

Where subjective judgements are made, it is stated whether they were made by the SR-Can team or 'experts', in which case the names of the experts accompany summaries of their judgments. This systematic approach followed by SKB is useful because it clearly identifies the data available for each parameter and how it has been used in the calculations.

Expert judgement, whether by individuals or panels, plays a role in determining PDFs for parameters in programmes that employ probabilistic assessments (e.g., the Netherlands, Sweden, the UK, and the US). The formal elicitation of expert judgements, particularly in a group setting, can be a labour-intensive effort, and is usually reserved for important parameters whose ranges cannot be determined easily from empirical data. The experience of previous EC-funded research on the use of expert judgement panels is that the methodology employed to process the judgements from individual panel members into joint PDFs is important to the success of the exercise [COSYMA 2000]. Currently Nirex favours a group expert judgement methodology that leads to a consensus PDF agreed between the experts present [Nirex 2006], while the DOE-YMP employs a maximum entropy approach to produce joint PDFs.

There is a close relationship between model and parameter uncertainty. This can sometimes be exploited to treat conceptual model uncertainties through a widening of the ranges for the PDFs of some parameters. An example of this is provided by NRG (the Netherlands), which also primarily uses a probabilistic approach to PA:

"*…the plastic behaviour of rock salt was modelled by an analytical model that was tuned by measurements and detailed FE calculations. This was necessary because measurements are only limited available and FE calculations are only possible idealised geometries. However, it was possible to cover the model uncertainty by using suitable bandwidths for the model parameters [EVEREST 1996]".*

This procedure provides a useful line of attack for difficult-to-treat conceptual model uncertainties, but should always be accompanied by a rationale setting out how it was done and why it is justified.

The limitations of formal probabilistic assessment methods when dealing with some types of uncertainties were explored in the EC-funded MUNVAR project [Robinson and Cooper 1995]. This reviewed the then state-of-the-art with respect to modelling with uncertainty and variability in all areas of technology that might be exploited for PA of radioactive waste disposal programmes. The conclusion was that methods used in advanced repository PA programmes, even at that time, were more highly developed than those in other fields. MUNVAR also identified several alternatives to traditional probabilistic assessment, and advocated further investigation of them. For example, the use of evidence-based systems has been taken up in more recent work, where it has been shown to offer a viable alternative to conventional methods for characterising epistemic uncertainty [Helton 2006].

3.4.1.2 Deterministic approach to treating parameter uncertainties

While a deterministic approach might seem simpler than the probabilistic one, in practice the deterministic approach is often more labour intensive and time consuming. Typically, deterministic calculations are performed running several codes in series, whereas in probabilistic approaches the whole system is implemented in a single model file. As a consequence, deterministic calculations require more effort in performing individual calculations, storing and organising data from sets of calculations, and feeding the output from models from one part of the assessment into another. These processes are not only labour intensive, they are also more prone to human error.

In programmes that primarily use deterministic models for PA, parameter uncertainties are treated by varying parameter values over a set of calculations performed for each fixed scenario. This can be done in a number of ways:

- By altering the value of a single parameter over its likely or possible range, thereby revealing the range of consequences due to uncertainties in individual parameter values.

- By using a number of different sets of parameter values.

- By employing uniformly conservative parameter values in a model run.

An example of how the use of different sets of parameter values is treated in a deterministic calculation is given by ANDRA [ANDRA 2005], where the parameter set used in a calculation is drawn from one of the following four types:

- *'A set of "phenomenological" values is considered to offer the best match between the model's results and the measured results. This choice must be supported by detailed arguments which may include a representative number of measurements, a physical reasoning that demonstrates that the chosen value is the most representative based on reliable data, or a judgement by recognised experts unambiguously designating it as the most appropriate value for the study context.*

- *'The set of "conservative" values is chosen among those generated by the studies and measurements which give a calculated impact in a range of high values, all other parameters being equal. In the simplest case, where the impact increases (or conversely, decreases) as the value of the parameter increases, a value in the highest (or lowest) range of available values. "Conservative" values cannot be defined if the variations in impact are not monotonic with changes in the parameter.*

- *'A set of "pessimistic" values is one that is not based on a state of phenomenological understanding, but is chosen by convention as definitely yielding an impact greater than the impact that would be calculated using possible values. Such values can represent physical limits. A pessimistic value can also be equal to the conservative value plus (or minus, where applicable)* *an appropriate safety factor that places it significantly beyond the range of measured values. A value cannot be described as "pessimistic" if the variation in impact in response to a variation in a parameter cannot be characterised.*

- *'In order to explore the possible parameter variation ranges, one or more so-called "alternative" values can be suggested as a means of investigating the effect of contrasting values.'*

A similar approach to parameter uncertainty is used in Switzerland, albeit with slightly different terminology. In Project Opalinus Clay [Nagra 2002a, 2002b], a "reference" set of parameter values was established for each combination of scenarios and conceptual models (Figure 2), along with several "alternative" sets. Within each scenario group, sub-groups of cases addressed alternative possibilities arising from conceptual model uncertainties. Individual cases within each subgroup addressed alternative possibilities arising from parameter uncertainties.

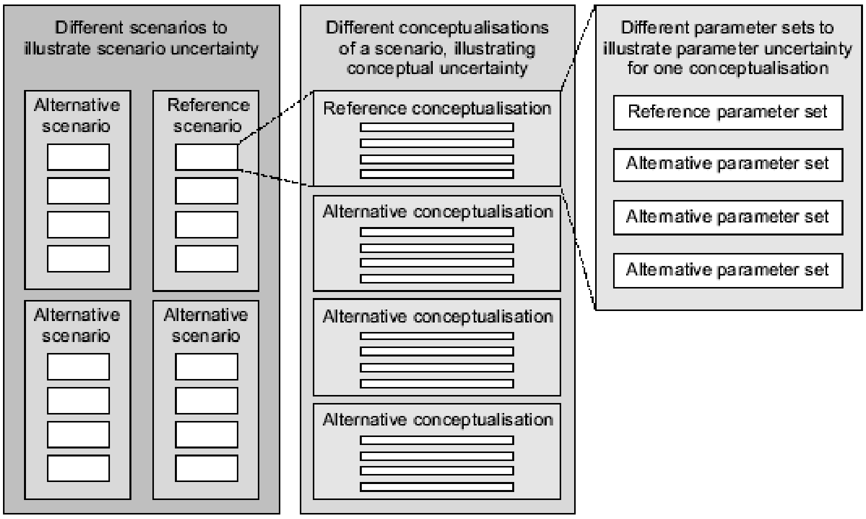

Fig 2. An approach to quantifying parameter, conceptual model, and scenario uncertainties for deterministic calculations (Project Opalinus Clay, Nagra, Switzerland).

One potential problem associated with this approach is the large number of separate deterministic cases that might need to be implemented, evaluated and presented. Making a large number of calculations within a deterministic assessment framework would be potentially time consuming, and post-processing all of the results in order to obtain meaningful conclusions about the relevance of uncertainty may not be a straightforward process.

3.4.1.3 Bounding case approach to treating parameter uncertainties

This approach does not attempt to quantify the most likely state of the whole system, but rather attempts to focus on extreme conditions that would threaten compliance with regulatory standards. There are transparency issues involved with this approach:

the consistent use of such models obscures the most likely outcomes and can give the impression that systems are less safe than they really are, resulting in unnecessary over-engineering, or rejection of adequate proposals.

In Finland, parameter uncertainty is primarily analysed by defining bounding analyses and sensitivity cases. In selecting the parameter values from databases (e.g. instant release fractions, solubility), POSIVA uses best estimate and conservative values. However, for certain important parameters in the biosphere assessment, a probabilistic approach is also used if appropriate well-established PDFs can be derived. For radionuclide transport of multiple radionuclides through several connected ecosystems, conservative assumptions are adopted.

3.4.2 Model uncertainty

We focus here on conceptual model uncertainty as there are long-standing tools available to treat uncertainty in mathematical models and computer codes (e.g., verification, benchmarking exercises, QA).

Conceptual model uncertainties, arising from an incomplete knowledge of the behaviour of engineered systems, physical processes and site characteristics, and their representation by simplified models, are perhaps the most difficult to quantify and least well covered in the programmes reviewed. Responses to the questionnaire indicate that they are often not treated explicitly. In fields of environmental modelling where it has been possible to compare predictions with measurements, albeit conducted over shorter time spans than those required for repository PA, the impact of conceptual model uncertainties on assessment endpoints has been shown to be significant [BIOMOVS II].

There are roles for a number of different types of model in PA. Detailed “process” models may be constructed for some subsystems in the assessment. These may be designed to demonstrate an understanding of key processes and investigate boundary conditions, as well as evaluating the performances of subsystems. However, no matter how detailed these models are, they will fail to represent some aspects of the real world that they attempt to represent. Less detailed models are usually used for the purpose of representing each subsystem in an overall framework for the PA. These models are designed to make the implementation of the whole assessment tractable. They will generally be based upon the more detailed process models, but will be more efficient to implement in computational terms. There is obviously potential for considerable variety in the way that system models may be constructed from subsystem models, in both probabilistic and deterministic approaches to modelling.

Confidence in conceptual models can be handled in a variety of ways, both quantitative and qualitative. Qualitative approaches to dealing with uncertainty are also discussed in Section 3.6 of this report. As an example, Nirex includes the following approaches for dealing with uncertainties in models of the natural system:

"Regarding consideration of geoscientific arguments for safety:

- *The most important argument is to present a clear understanding of past geological evolution at the particular site, consistent with the global understanding of geological evolution. Efforts should be made to achieve a broad consensus on this from many independent experts.*

- *The supporting arguments are seldom based on a single piece of evidence. It is the chain of arguments rather than individual arguments that is important.*

- *A primary interest is in "reasonable" predictability of the geological system. It is recognized that most geological systems evolve with time, but all details of this are not needed for demonstrating safety. However, there is a need to find well-reasoned bounds for the future evolution.*

- *Generally, the same type of arguments can be applied for different rock types. The strength of arguments and the time scale of validity, however, vary between host rocks and types. The arguments work better in "simple" systems.*

- *Sharing experiences between different programs is crucial in assessing strengths and weaknesses in "own" arguments."*

The actual approach adopted to handle conceptual model uncertainties will be partially determined by the constraints of budget and timetable. It is possible to argue that total system probabilistic approaches (TSPA) to PA face particular challenges with respect to treating conceptual model uncertainties, since a great deal of effort is invested in a fixed, single implementation of the entire system. While it is possible to treat conceptual model uncertainties by implementing alternative subsystem model conceptualisations within the implementation for the whole system, in practice this may not be an attractive option. An alternative quantitative approach, already discussed in Section 3.3, is to widen parameter PDFs through the use of expert judgment so as to represent a greater range of uncertainty than that accounted for by uncertainty in the parameter values themselves. This approach appears to be commonly used, and is referred to by several questionnaire respondents. However, unless there is a process for directly mapping parameter values to specific alternative conceptualisations, this approach begs some difficult questions. In order to use it there must be some understanding of the effects on assessment endpoints of altering individual parameter values, and a feeling for how much effect conceptual model uncertainties can have on the same assessment endpoints. It is possible that deterministic calculations based on the use of alternative models and designed to scope the effect of conceptual model uncertainties can be helpful in this respect.

With regard to the probabilistic PA performed for the WIPP, SNL states that there assumed to be no uncertainties associated with the implemented models (conceptual, numerical, etc.). Within this stated approach, nevertheless, conceptual model uncertainties are partly addressed through adoption of conservative assumptions.

In common with SNL-WIPP, the primary approach used by DOE-YMP has been probabilistic. The probabilistic assessment methodology and endpoints are specified in site-specific regulation. PA models used to demonstrate compliance are generally abstractions of detailed process models. The PA models thus consist of abstractions of detailed process models "quilted" together; these are represented either through explicit formulation or "response surfaces" generated by earlier calculations. Expert panel elicitation methods are widely used to derive shapes and ranges for PDFs that reflect the epistemic uncertainties in the parameters themselves, and any widening that may be required to account for uncertainty arising from the abstraction from detailed process models.

In both the UK and the US, conceptual model uncertainties have been considered by conducting a "bias audit". "Biases" are effects on calculation endpoints that arise from processes and spatial and temporal variations that the implemented model does not address. Biases are estimated by a combination of expert judgement and deterministic scoping models. For example, in the UK regulator's Dry Run 3 project, the main aim was to apply an existing probabilistic methodology to address future environmental change. As part of the project, a "bias audit" was conducted [Thorne 1992], which looked at issues that arose from conceptual model uncertainty. The approach was taken further in a successor project, the regulatory assessment of the Sellafield site in the early 1990s, and is still seen as part of the Nirex (UK) approach to considering uncertainties in PA.

In the Netherlands, conceptual model uncertainty is addressed by external reviews and comparisons with other studies (benchmarking). The NRG response to the questionnaire provides the example of the PDF of the subrosion rate of a salt dome to demonstrate how a PDF for a parameter can be widened to account for conceptual model uncertainty. Derivation of the subrosion rate for a candidate site for deep geological disposal would be based on long-term measurements carried out on a large number of similar salt domes. The derived rate has to be regarded as a simplification of several geophysical processes that determine the spatial development of a salt dome. The PDF set for the derived rate will be determined to some extent by the conceptual models used to interpret the measurement data.

Deterministic approaches to PA appear to offer greater transparency in treating conceptual model uncertainties, since they consist of a large number of self-contained, tailored calculations, based on separate models for each part of the PA. In this situation it is relatively easy to change a submodel for a particular part of the PA and to identify the impact on assessment endpoints, in the manner suggested by the scheme for treating uncertainties employed by Nagra in Project Opalinus Clay (Figure 2).

An example is the use of two alternative models for the dissolution of the fuel matrix [Nagra 2002b]. In the reference conceptualisation, the rate of dissolution of the SF matrix is assumed to be controlled by the generation of radiolytic oxidants. In the alternative "solubility limited dissolution" conceptualisation, reducing conditions are assumed to prevail at the surface of the SF matrix, irrespective of the generation of radiolytic oxidants. This alternative conceptualisation results in a fractional fuel dissolution rate that is approximately two orders of magnitude lower over the time interval 10^4 - 10^6 years post-closure.

In a probabilistic approach, two independent probabilistic assessments would be needed, or the two different model conceptualisations could be translated into two values for a single model parameter, or a model parameter could be used to "sample" the two alternative conceptualisations as part of a single probabilistic implementation. For example, in the case discussed above, the two conceptualisations could be implemented in a probabilistic model through modifying the PDF for the fuel dissolution rate, or by assigning a probability to one model (say 0.75) and one minus that probability to the other model (0.25). However, care is needed in this approach to ensure that the relative importance and source of uncertainties in the system output is described clearly.

3.4.3 Scenario uncertainty

A significant part of a PA will deal with the evolution of a waste disposal system. "Scenarios" are a useful way of conceptualising the evolution of a system through considering a set of alternative futures for the system. In most of the programmes providing responses to the questionnaire, the safety of geological disposal systems is assessed using multiple scenarios. The process by which these scenarios are identified, known as "scenario development", typically contains four basic steps:

a) Identify and classify all phenomena (i.e. FEPs) potentially relevant to the performance of the disposal system.

b) Eliminate FEPs according to well-defined screening criteria.

c) Form scenarios from FEPs in the context of regulatory performance criteria

d) Specify scenarios for consequence analysis.

Scenario development typically involves a structured approach to screening to establish those FEPs included in post-closure system assessment modelling, those FEPs which can be defensibly excluded, and those FEPs for which defensible screening arguments cannot be presented, but which are not included in the PA modelling. The process of scenario development cannot be automated and is heavily dependent on the use of expert judgement, formal or otherwise.

Recent work on scenario development methodologies has led to increasing use of the concept of safety functions. The aim in these methodologies is to identify deviations from an expected evolution scenario, based on the failure of one or more safety functions. For example, in work undertaken recently on behalf of ONDRAF/NIRAS, the initial stage of the methodology uses a list of initiating FEPs to identify potential failure of the safety functions provided by the components and barriers of the disposal system. These potential failures are identified from a functional diagram for the expected evolution scenario, based in turn on the implementation of a disposal system design at a particular site and phenomenological studies. In the second stage of the scenario development methodology, altered evolution scenarios are developed by considering the timing of FEPs, their consequences in terms of safety function effectiveness, and the status of other safety functions.

All of the respondents address "scenario" uncertainties in some way in their PA methodologies. Two main types of approach may be delineated:

1. A pure probabilistic sampling approach, in which scenario occurrence is sampled from a distribution of possibilities during a Monte Carlo calculation in much the same way that parameter values are sampled from PDFs. This approach was developed at SNL about 20 years ago, and is currently the PA methodology prescribed by regulation for the WIPP facility. The PA produces many thousands of 'futures' for each set of parameter values, which are then combined in the form of a CCDF of cumulative releases to the accessible environment over 10,000 years. The treatment of scenario uncertainty using a probabilistic approach has also been investigated in other countries in the past, including Canada [Stephens and Goodwin 1990] and the UK [Sumerling 1992]; however, these approaches are no longer in use in these countries.

2. Evaluation of a limited set of deterministically defined scenarios, currently practiced by almost all of the countries participating in this study. Although individual scenarios are defined deterministically, scenario consequences may then be assessed probabilistically or deterministically. Probabilistic assessment means a deterministic approach is taken for "irreducible" uncertainties associated with development of the system over time (scenario uncertainties), and a probabilistic approach for "reducible" uncertainties associated with knowledge of the system (many parameter and conceptual model uncertainties).

   Among the types of scenarios that are typically considered in such an approach are:

   a) The reference or normal evolution scenario, which is usually the scenario with the greatest probability of occurrence.

   b) Altered evolution scenarios, in which the impacts of more unlikely future conditions are evaluated. They are sometimes implemented using a pessimistic "bounding" approach to demonstrate compliance with regulations and to build confidence in safety.

   c) "Stylised" scenarios for some events and processes for which prediction is not possible. In particular, this technique is often used to assess potential impacts associated with future human intrusion scenarios. In this case, one or more illustrative calculations are performed for a deliberatively prescribed situation (e.g., drilling based on current technology at one or more future times), with limited or no consideration of possible future human developments and limited or no consideration of when such an event might actually occur and how likely such a scenario might be.

> It is possible to add more types of scenarios to this list by dividing or reordering the categories. For example, the AVN (Belgium) response lists five basic types of scenario that they consider in deterministic PA, including "altered evolution", "beyond design limit", and "what if" scenarios. These three examples might all be taken to be refinements of category 2b above.

In addition, some programmes (e.g. Belgium, UK) consider the use of a discrete set of assessment timeframes (e.g., first few hundred years, thousand years, hundreds of thousands of years) in structuring the assessment, in developing assessment models, and in communicating the results.

3.5 Sensitivity Analysis and Uncertainty Analysis

- *How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis?*

A large amount of research on the use of sensitivity analysis techniques in PA will be conducted as part of RTDC2, including a detailed evaluation of alternative methods for sensitivity analysis, so respondents were deliberately not asked to provide detailed information on techniques for sensitivity analysis. The responses to this question did, however, indicate that the value of sensitivity analyses is widely appreciated in PA and safety case development, and a clear, well-understood distinction is made between sensitivity analyses and uncertainty analyses.

The purpose of uncertainty analysis is to give an absolute estimate of uncertainty in assessment endpoints such as dose or risk. It is achieved by propagating through the assessment system estimates of uncertainty in the inputs. The analysis produces estimates of uncertainties in key predicted quantities without necessarily explaining which input quantities the uncertainties are derived from.

The purpose of sensitivity analyses is to understand how the system works and which parameters have a strong influence on assessment endpoints. This leads to the identification of those sources of uncertainty in parameter values or conceptual model implementation where the most benefit would be gained – in terms of reduction in overall uncertainty or greater confidence in PA results - from further investigation or modelling.

A variety of methods for conducting sensitivity analyses is available, ranging from simply modifying individual parameter values in deterministic calculations, to more complex formal schemes such as the regression analysis/classification tree analysis/ entropy analysis approach used by the DOE-YMP, the IFFD scheme developed by OPG [Melnyk *et al.* 2006], and differential sensitivity coefficients [Khursheed and Fell 1997].

Given the ambiguity in the phrasing of the question, only the DOE-YMP provided a detailed discussion of techniques used for sensitivity analyses. The probabilistic approach to TSPA lends itself to the use of formal sensitivity analysis schemes for unravelling the relationships between TSPA results and model inputs. A detailed description of the DOE sensitivity analysis methods can be found in the DOE questionnaire response in the Appendix.

3.6 Supporting Arguments and Qualitative Methods Used to Address Uncertainties and Provide Confidence

- *What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety?*
- *What measures other than numerical analysis can be utilised to manage the uncertainties?*

These two questions, asked separately in the PAMINA 1.2 questionnaire, are clearly related. Questionnaire responses are consequently discussed here in a single, combined section. Respondents identified three non-numerical or qualitative strategies for managing uncertainties in PA and the safety case:

1. Robust design (most programmes).
2. Qualitative assessment methods (most programmes).
3. Implementation of QA for development of the PA and safety case (e.g., Japan, Spain, Switzerland, UK, US).

These strategies are discussed in turn below.

3.6.1 Robust design

Uncertainties are managed in many programmes by using conservative engineering design principles. For example, this is expressed in the response from Germany as the adoption of:

"…classical engineering methods, e.g. a safety oriented repository design (safety design), improvement of the natural system, proof of structural reliability of important design elements to reduce variation ranges of their safety related characteristics, and QA".

The response from IRSN (France) identifies examples of this type of engineering approach:

- *"…limitation of high temperatures to preserve favourable and known physical and chemical environment (the envisaged repository concepts should prevent rises in temperature that could prejudice the containment capabilities of the repository components, adoption of an over-pack is relevant to prevent releases of activity in temperature conditions where transport phenomena are poorly controlled…)*

- *seals designed with narrow trenches to intercept EDZ*
- *dead end architecture of disposal tunnels*
- *location of shaft and repository areas with respect of mapped structures and underground flow patterns"*

As another example, the approach in Finland and Sweden is to ensure that the engineered barriers used in the KBS-3 concept are extremely robust, thereby making uncertainties associated with the far field and biosphere easier to discount.

3.6.2 Qualitative assessment methods

In addition to numerical simulations of repository performance, safety cases also employ qualitative assessment methods to convince a broad range of stakeholders that a deep geological repository will be acceptably safe. Programmes in many countries employ qualitative assessment methods, and in some programmes they are considered to be as important as the quantitative methods. This is particularly true where an assessment considers events far removed in space and time from the original emplacement of waste in the repository, and there are very large uncertainties associated with the quantitative assessments.

For example, following government rejection in 1997 of the Nirex submission to build an underground laboratory at Sellafield, the UK programme took a step back and has looked hard at supporting arguments. The Nirex response on this subject was particularly illuminating, and a substantial part of it is quoted below:

"Qualitative arguments can include:

- *Comparisons with natural analogues, i.e. occurrences of materials or processes which resemble those expected in a proposed geological waste repository, for example the Maqarin site in Jordan which provides a natural analogue for a cementitious repository.*
- *Showing consistency with independent site-specific evidence, such as observations in nature or palaeohydrogeological information.*
- *Evidence for the intrinsic robustness of the repository system, for example demonstrating that relevant features and processes are well understood, often supported by evidence from underground research laboratories.*
- *Describing the passive safety features of the repository and demonstrating that the design uses best practice scientific and engineering principles.*
- *The safety case may also include more general arguments related to radioactive waste management, and information to put the results of performance and safety assessments into perspective. For example, for the Nirex concept a repository at a depth below ground of about 650m is assumed.*

Such a depth offers a number of benefits to the long-term management of radioactive waste that would be of relevance to the safety case.

"There is also a role in many performance assessments for semi-quantitative arguments, for example applying physical and chemical understanding of the system to build more simple models to give an insight of repository system behaviour.

"Qualitative arguments may be particularly important in performance assessments conducted at the earlier stages of a repository development programme. At these stages the focus is on building understanding of the processes that could affect the performance of a repository and on explaining how the repository concept will be able to provide safety over very long time periods. There may also be insufficient data at this stage to justify complex calculations, therefore other methods are required to build confidence in the viability of the proposals. Assessments at this stage are also more likely to be communicated, at least in summary form, to wider, non-technical audiences for whom qualitative arguments may be more meaningful than detailed, complex calculations.

"A safety case contains a number of different elements, and is an integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of a radioactive waste management facility. A performance assessment in support of a safety case will include a range of quantitative performance indicators, together with alternative lines of reasoning and qualitative considerations, such as the intrinsic quality of the repository design, to build understanding in the overall repository performance and hence determine whether it satisfies the relevant safety requirements."

In Finland, a wide-ranging, multi-dimensional uncertainty analysis approach has been outlined for the biosphere assessment. The approach combines traditional uncertainty and sensitivity analysis with methodologies for quantifying non-numerical uncertainties, such as "pedigree analysis" for the evaluation of uncertainties in the knowledge base. The methodology might be extended to other areas of the safety case after more experience on the practical implementation for the biosphere has been gained.

The response to this question from Germany points to work done on alternative lines of argument in the EC SPIN project (Testing of Safety and Performance Indicators):

"Additional safety indicators, such as radionuclide flows and concentrations, can improve the safety statement by excluding a complete field of uncertainty, e.g. all uncertainties relating to the biosphere, and using completely different safety measures. This has been tested in the SPIN project [Becker et al. 2003]."

In France, a combined quantitative / qualitative approach was taken in the safety case for the Dossier 2005 [ANDRA 2005]. A qualitative safety analysis methodology was developed for detailed consideration of FEPs. The qualitative safety analysis is a method for verifying that all uncertainties in FEPs and design options have been appropriately handled, thereby justifying the selection of altered evolution scenarios.

In the US, the mainstay of the safety case is a probabilistic PA, strongly influenced by detailed prescriptive regulation. It can be argued that a prescriptive and detailed regulatory regime could limit the scope and, indeed, the need for supporting arguments in the compliance assessment, if the regulator does not consider/ask for them explicitly. Supporting arguments used by DOE-YMP include building confidence by:

"…demonstrating robust multiple barriers, using natural analogs where appropriate, showing that a detailed characterization of the repository has been performed at the component and system levels, comparing intermediate results from the system-level model with process model results, comparing with other comparable system-level analyses where appropriate, peer reviews, and also institutional actions including performance confirmation monitoring, site controls, QA, and assuring a safety-conscious work environment."

3.6.3 QA systems

Implementing appropriate QA systems for conducting repository development programmes (including PA, design, site characterisation, programme management, etc.) plays a part in the process of building a compelling safety case and obtaining approval from regulators and stakeholders. Questionnaire responses indicate that many programmes have applied custom-designed or internationally accredited QA procedures to their operations. Examples illustrating the range of responses are given below.

ANDRA (France) and Nirex (UK) are accredited to ISO 9001 [ISO 9001]. ISO 9001 is a general-purpose QA standard, intended for use in any organisation that designs, develops, manufactures, installs and/or services any product or provides any form of service. It provides a number of requirements that an organisation needs to fulfil if it is to achieve customer satisfaction through consistent products and services that meet customer expectations. In this case, the "customer" might be considered the regulator and other stakeholders.

NUMO (Japan) has developed its own structured QA approach:

"In order to maintain flexibility without losing focus and make the work more systematic, NUMO has developed a formalised tailoring procedure, termed the NUMO Structured Approach (NSA)[4]. The NSA provides a methodology for developing repository concepts in an iterative manner, which couples management of immediate issues with consideration of longer-term developments. The NSA also guides the interaction of the key site characterisation, repository design and Performance Assessment groups and is facilitated by tools to help the decision-making associated with the tailoring process (e.g. a requirement management system, RMS) and with comparison of siting and design options (e.g. multi-attribute analysis). The RMS is being developed to help implement the NSA. This RMS will allow the justifications, supporting arguments and knowledge base used for every decision to be clearly recorded and will highlight when such decisions may need to be revisited, for example due to changing boundary conditions or technical advances. It thus serves as

a valuable tool to keep track of the wide range of constraints on designs, while the entire process runs within an overarching Quality Management System (QMS). NUMO has developed its own QMS to ensure high quality of all its technical activities, documents and databases. The QMS will be integrated within the RMS, to ensure the total quality of the repository project, including the safety case development [4]".

The SNL-WIPP (US) response states that:

"Thus efforts to demonstrate the overall credibility of the approach used in the assessment are likely to be important. These efforts include such things as configuration control for all related computer files, documentation of changes and their impacts, verification and validation of the models, use of formalized methods for assessing uncertainties subjectively, peer review down to the level of the code, etc. Putting these additional activities under QA can help to confirm that the approved methodologies are being used. However, care must also be taken to help ensure that the requirements and delays imposed by QA do not detract from the quality of the assessment."

3.7 Key Uncertainties and Likelihood of Challenging the Project

- *What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?*

Responses to these questions indicate that there is a wide variation in what are considered key uncertainties in different programmes. Uncertainties on a broad range of performance measures are cited as having the potential to impact the progress of projects. Much of this variety arises out of the different stages that programmes are in their development and the diverse range of repository concepts and host rock formations in the programmes.

The broad range of responses and absence of widely identified 'problem' uncertainties may be interpreted as indicating confidence that it is possible to dispose safely of long-lived radioactive wastes in appropriately engineered and sited deep geological repositories. However, a note of caution should be sounded, since organisations whose remit is to implement a deep geological repository – all but two of the respondents – may be more sanguine than other stakeholders, such as regulators and members of the public, and see fewer issues that might impede progress.

ENRESA (Spain) considers that, although there remain some open issues that need to be properly addressed (gas generation and transport, colloids, etc.), in the PA exercises performed to date no uncertainties have been identified that could jeopardise the programme. These statements reflect ENRESA's confidence in the robustness of geological disposal as a long-term management option for radioactive waste:

"The Safety Assessment exercises for repositories in both granite and clay rock were done assigning wide ranges of values to most parameters, and doses were found to be well below the acceptance criteria. None of the individual runs of the probabilistic calculations leads to doses greater than 3% of the reference value (10^{-4} Sv/yr). In the future, when more data (mainly site specific) become available, uncertainty ranges are expected to decrease but remain bounded by those already used. Doses will be bounded by the estimates already performed too. As a consequence, we do not think that uncertainties could jeopardise the project in future stages of development."

ONDRAF/NIRAS (Belgium) singles out uncertainties in calculated maximum dose associated with the speciation and migration of Se-79 in Boom Clay as a particular concern, as well as uncertainties in the radionuclide inventories for HLW, which arise from different burn-ups and levels of enrichment. The Engineered Barrier System (EBS) behaviour and performance is also a source of uncertainty, which will be the subject of future work.

Uncertainties around long-term evolution of the EBS are also a concern in Germany. However, here the issues are different than those in Switzerland, because of the salt host formation. The Excavation Damage Zone (EDZ) and design of the EBS are likely to play a decisive role in the evolution of brine intrusion scenarios. The main challenge to the programme, however, is perceived to be from communicating with members of the public, rather than from intractable technical issues.

In Sweden, where the candidate sites are situated in crystalline rock host formations, the following three examples of potentially important uncertainties are given by SKB:

1. The extent of buffer erosion/colloid release when exposed to dilute groundwaters during glacial conditions.

2. The hydraulic interpretations of the candidate sites.

3. The extent of thermally induced spalling in the host rock near the deposition holes.

The first of these, if unresolved, is perceived as being a threat to the programme timetable.

Uncertainties relating to the EBS are also highlighted by Nirex (UK) in their 'Viability Report' [Nirex 2005]. The following outstanding uncertainties were identified:

"C-14 has been identified as a key issue in the PGRC [Phased Geological Repository Concept]. *Calculations have been carried out to scope the potential impact of C-14 for two alternative scenarios. In the first of these it is assumed that C-14 all dissolves in groundwater and is released to the biosphere in solution; in this case the calculated risk is well below the regulatory target. The second scenario assumes that carbon-14 is released as gas and all methane generated is released directly to the biosphere as gas, taking no account of any delay in the geosphere. In this case, the calculated risk is significantly over the regulatory target. In practice, some of the gas*

could dissolve in groundwater and the migration of gas in the geosphere would depend on the site geology. In many geological settings, some form of gas retardation may be expected.

"Nirex has an ongoing programme of research on C-14, which is improving our understanding of these issues. Further work is still required, which includes: work to assess the extent to which gas would dissolve in groundwater; work to assess the extent to which different geological environments have the potential to retard gas migration; and work to reduce uncertainties in the rates and quantities of gaseous C-14 generated.

"Non-aqueous phase liquids (NAPLs) are challenging because they can have a greater capacity for uptake of some radionuclides and may migrate more rapidly through the geosphere than groundwater. NAPLs would only leave a repository vault if there was sufficient pooled in the vault to overcome the forces that prevent such materials entering narrow fractures in the host rock".

With respect to the EBS, a difficult question to answer is whether a focus on uncertainties associated with the EBS arises in some disposal programmes because these lead to most uncertainty in key performance indicators, or because it is the one component of the disposal system that is most under human control, particularly after potential sites have been chosen.

In contrast, NRG (the Netherlands) have identified hydrology and the extent of dilution in the biosphere as key uncertainties for a salt-hosted repository:

"The PROSA probabilistic study has shown that large uncertainties arise from the hydrology in the overburden and in the amount of dilution in the exposure pathways in the biosphere. It is inherent in the disposal concept that engineered barriers and the near host rock must behave very reliable, which explains why these important parts of the disposal system do not dominate the uncertainty.

"Example: The hydrology in the overburden, as well as the dilution in the biosphere are depending on far future climatic conditions. Within the next 100 000 years one or more ice ages are likely to occur. However, climatic models are unable to predict when. This causes a very broad bandwidth in possible local climatic and hydrological conditions.

"It should be noted that the strength of the disposal concept is found in the reliable behaviour of the engineered barriers and the near host rock, as these systems are not affected by e.g. an ice age."

The response from SNL-WIPP (US), based on another salt-hosted repository concept, concurs that the EBS is not the largest source of uncertainty for salt-hosted repositories. Instead, uncertainties associated with future human activities are identified, specifically those associated with drilling intrusion scenarios:

"The key long-term performance measure for the WIPP is the total cumulative release of radioactivity to the environment. Solid waste material removed from the repository

by the drill bit and shearing forces of the drilling fluids during a drilling intrusion account for an overwhelming majority of the total releases. These solid waste materials are termed "cuttings and cavings." Uncertainty in total normalized releases is largely due to uncertainty in waste shear strength. In fact, shear strength accounts for more than 88% of the variability in total releases. The uncertainty in the volumes of cuttings and cavings is primarily controlled by shear strength. The second most important variable is a "solubility multiplier" that represents uncertainty in solubilities for all actinides in the +III oxidation state. This variable accounts for approximately 2% of the variability in total releases. The drill string angular velocity, also used in computing cuttings and cavings, contributes to about 1% of the variability of total releases. Each of the remaining parameters explain less than 1% of the variability in the total releases."

The host formation of the WIPP and regulation are important factors in these conclusions, since assessments need to be based on past rates of drilling, and the site is located in a resource-rich area.

Nagra (Switzerland) indicates that there is confidence that the initial characteristics of the disposal system, as well as its evolution, are generally well understood. The safety assessment did not identify any outstanding issues or uncertainties with the potential to compromise safety. Nevertheless, a number of topics are listed that are subject to further research and development to further strengthen system understanding and to further reduce uncertainties [Nagra 2002a, Section 8.4]. One of these topics is directly linked to the "tight" host rock Opalinus Clay: the generation, and transport through the engineered barriers and the host rock, of gas originating from the corrosion or decomposition of the emplaced waste.

NUMO (Japan) also considers that uncertainties associated with the geosphere are currently of greatest concern.

In conclusion, almost no organisations identified uncertainties that may challenge programmes, suggesting a high level of confidence in respondents' ability to site and design deep geological disposal facilities so as to manage uncertainties effectively. However, respondents variously identified the engineered barrier system, the geosphere, the biosphere, and future drilling activities as key sources of uncertainty that require further investigation. Much of this variety arises out of the different stages that programmes are in their development and the diverse range of repository concepts and host rock formations in the programmes, but may also point to the need for objective methods for determining which part of the PA dominating uncertainties arise from.

3.8 Using Uncertainty Analysis Results to Focus Future Work

- *How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work?*

The responses to this question indicate that there is widespread awareness that identification and management of uncertainties is an iterative process that can lead to a stepwise reduction of uncertainties in PA. However, there are variations in the degree to which this awareness has been translated into concrete elements of programmes.

A powerful tool in the iterative process for evaluating knowledge-based (epistemic) uncertainties in PA is sensitivity analysis. An example of a structured use of sensitivity analyses taking place within a probabilistic assessment framework is provided by the SNL-WIPP project (US):

"During late site characterization and early Performance Assessment development, the project performed a systems prioritization where Performance Assessment tools were used to determine the sensitivity of parameters under investigation to Performance Assessment outputs. This information was used to prioritize experimental and other site characterization work that was ongoing with the intent of developing or justifying Performance Assessment parameters. Highly sensitive elements were given priority while less sensitive elements were reduced or eliminated. This prioritization resulted in better management of resources and expedited the final Performance Assessment and compliance certification application.

"After the site was operational, sensitivity assessments, operational efficiency changes and other drivers led the project to investigate many Performance Assessment related elements such as ground water level anomalies in the WIPP vicinity and refinements in models and computer codes to increase efficiencies and assess changes to the repository designs. This type of information is necessary for periodic compliance recertifications and change requests."

The emphasis here is on reducing knowledge-based (epistemic) uncertainties through further investigations, model refinement, and consideration of repository design modifications. Other responses, such as that from Germany, place a greater emphasis on reducing uncertainties through engineering design. In choosing a strategy, factors to weigh will include "how reducible" the uncertainties are, the likely effectiveness of engineered solutions, and costs associated with both strategies. In addition, for an operational repository such as the WIPP facility, some aspects of the design will be frozen, and there is less scope for design modifications.

3.9 Communication of Uncertainty

- *What works best in communicating the different types of uncertainty to regulators and to other stakeholders?*

Responses to this question were patchy: some respondents profess to have little experience in this area, while others chose not to answer the question. Some restricted themselves to discussing communications with regulators, and only a few programmes have gone as far as commissioning research into different approaches to communicating uncertainty.

In Sweden, a variety of methods have been used to communicate assessment outcomes, although no best method has been identified. The following examples of good practice are quoted [referring to SKB 2006a, 2006b]:

- "*Data uncertainty as simple box and whisker plots or cumulative distribution functions, see e.g. Figures 9-25 and 9-30 of SKB TR-06-09 [SKB TR-06-09]*

- *Output data uncertainty for a particular calculation case as percentiles of dose as a function of time, see e.g. Figures 10-16 and 10-17 of SKB TR-06-09*

- *Impact of conceptual uncertainty as comparisons of mean values as a function of time of probabilistic calculation results using different assumptions, see e.g. several Figures in section 10.5.7 of SKB TR-06-09*

- *A clear verbal description/interpretation of the results is often more important than the particular technique used when presenting the numerical results*."

In the UK, research has been commissioned by Nirex and other government agencies on the question of how best to communicate risk and uncertainty associated with radiation exposure and repository PA. The overall conclusion from research carried out for the UK Food Standards Agency [FSA 2003, FSA 2004] was that the appetite of the public for information on individual dose/risk exposures is small, and that a non-technical audience poorly understands the concept of dose.

With respect to how best to communicate uncertainties in assessments, Nirex states that:

"*…the regulatory guidance in the UK leads the developer to a probabilistic approach, so such an approach is of most value in communicating the uncertainties to the regulators.*

"*Scientific uncertainty can undermine public confidence in environmental and technological projects. However, one of the ways that scientists can undermine confidence in their work is by maintaining an exaggerated sense of certainty. Therefore, it is important to be open and honest about uncertainty, and to explain how it is managed and why it is still possible to have confidence in the assessments and the proposed facility.*

"Explicitly stating the uncertainties associated with assessments will enable stakeholders to develop more informed responses to the situation. It will also help them to engage in the debate and feed back important information about their issues of concern. This could influence the scenarios that are assessed or enable measures to be put in place to lessen the socio-economic impacts of any uncertainties or risks."

4 Issues for Further Research

4.1 Questionnaire Responses

An important aim of this synthesis report is to inform and focus discussion on the implementation plans for RTDC2 tasks at the workshop held in Brussels in March 2007, and beyond. Responses to the final question posed in the questionnaire are synthesised in this part of the report:

- *What are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc.?*

The following issues were raised in the questionnaire responses; several of these issues cut across the RTDC2 work programme and, indeed, the entire PAMINA work programme. We identify parenthetically where the issue is likely to be dealt with in the PAMINA work programme.

- What further regulatory guidance is needed on the treatment of uncertainty? (Task 2.1.A)
- How can uncertainty overall best be communicated to stakeholders? (Task 2.1.B)
- How can the increase of uncertainty with time post-closure best be managed and communicated? (first part not explicitly considered, second part Task 2.1.B)
- How can all uncertainties best be combined in a coherent and consistent way, and how can the adequacy of the approach be demonstrated? (partly covered in Task 2.1.C and Task 2.2.E)
- What is the best means for the conduct of sensitivity and uncertainty analyses? Is it possible to derive unique rules for establishing parameter distributions, or for quantifying the degree of parameter correlation, or for undertaking probabilistic uncertainty analysis? (Task 2.1.D and Task 2.2.A)
- Can the potential couplings between detailed process models of different subsystems be adequately represented so as to help justify the use of simplified TSPA models? (partly covered in Task 2.2.B and in RTDC3 and RTDC4)
- What procedures work best for formal use of expert judgement to develop PDFs (quantitative inputs) and to develop scenarios (qualitative inputs)? (Task 2.2.A and Task 2.2.C respectively)

- What are appropriate means for upscaling data to derive parameter values for use in PA, especially for the far field? (Task 2.2.D)

Therefore, a significant conclusion from the review is that the RTDC2 tasks set out in the PAMINA contract Annex 1 are well targeted, and appear to cover nearly all of the topics of greatest interest to questionnaire respondents. A few possible modifications to the work programme are discussed under individual RTDC2 tasks in Section 4.2.

4.2 Key Discussion Points for RTDC2 Tasks

In order to promote focused discussion at the March 2007 workshop and to further the implementation of RTDC2 tasks, more detailed discussion points were identified for each task as part of the WP1.2 review work. We provide below for each task a brief statement of objective, followed by the list of questions. The results of discussions at the workshop are summarised in terms of revised implementation plans developed for each task [Galson Sciences Limited 2007].

4.2.1 Task 2.1.A: Regulatory compliance

This task focuses on how the treatment of uncertainty in PA impacts upon regulatory compliance. The research will be undertaken by holding a facilitated workshop to be attended by regulators and regulatory support organisations from different European countries with different approaches to regulation of radioactive waste.

For discussion:

1. What are the advantages and disadvantages of detailed, prescriptive regulation for deep geological disposal and treatment of uncertainty?
    a. Guidance on receptors and regulatory endpoints?
    b. The balance between quantitative PA and additional (qualitative) lines of reasoning?
    c. Strategies for minimising the impact of uncertainties on decision-making?
2. What is the relationship to a stepwise approach to licensing?

4.2.2 Task 2.1.B: Communication of uncertainty

This task will aim to assess the effectiveness of different methods for communicating disposal system performance, communicating how it has been determined, and communicating the uncertainty associated with the determination and its significance.

For discussion:

1. What is best practice in communicating uncertainty (and confidence) to different stakeholders?

4.2.3 Task 2.1.C: Approaches to system PA

This task will examine the relative advantages and disadvantages of different approaches to the quantification of uncertainties in system-wide PA calculations.

For discussion:
1. Under what circumstances is it appropriate to use probability to treat uncertainty, and under what circumstances are deterministic approaches more appropriate?
2. At what stage of repository development should assessments aim to be more conservative or more realistic?
3. Do hybrid approaches such as "fuzzy" mathematics, possibility theory, interval mathematics, evidence-based theory offer any advantages over standard probabilistic approaches?
4. What alternatives are there to presenting the results of PA and associated uncertainties?

4.2.4 Task 2.1.D: Techniques for sensitivity and uncertainty analyses

This task will involve review, analysis and testing of the methods of sensitivity and uncertainty analysis applied to PA calculations. The work will proceed through parallel studies undertaken by different groups.

For discussion:
1. What are the main techniques in use and what are their strengths and weaknesses?
2. How will the parallel case studies be organised and synthesised to produce a deliverable that can feed into WP2.3?
3. How will test cases be conducted so that objective measures of suitability are gained?
4. Why do different programmes identify key uncertainties in different parts of the PA?

4.2.5 Task 2.2.A: Parameter uncertainty

This task will involve research into the development of practical recommendations for the reliable and defensible derivation of PDFs for key parameters used in PA calculations. This will involve testing the limitations and (dis)advantages of alternative methods such as statistical analysis, Bayesian approach, expert judgement, and hybrid methods.

For discussion:
1. What is best practice for identifying and implementing parameter correlations in PA?
2. What is best practice for deriving PDFs?
3. What is the link to related work in WP4.3 (uncertainty analysis)?
4. What is best practice for using expert elicitation techniques to derive PDFs?
5. How will the impact of PDF shape on results be assessed?

6. What are the plans for synthesising multiple case studies / subtasks to produce a deliverable that can feed into WP2.3?

4.2.6 Task 2.2.B: Model uncertainty

The task will evaluate methods for treating uncertainties in PA calculations arising from the representation of physical processes by models, at both conceptual and practical levels. It will include studies that use alternative representations of key processes such as dissolution/solubility, radionuclide retardation, gas migration and groundwater flow, in PA calculations.

For discussion:

1. How will the identified conceptual modelling uncertainty issues be tested (gas pathway issues, model complexity case study, radionuclide transport issues)?
2. What is the link to related activities in WP3.2 (PA and gas migration), WP4.1 (PA and model complexity), and WP4.2 (PA and geometric complexity)?
3. Is it desirable or possible to apply a consistent approach to model evaluation across every part of a PA?
4. How valid is the practice of treating conceptual model uncertainties through widening parameter ranges?

4.2.7 Task 2.2.C: Scenario uncertainty

This task will evaluate the uncertainties attached to scenarios, including the extent to which probabilities of scenarios can be evaluated, methods for amalgamating consequence results into risk assessments and the associated limitations (e.g. related to statistical convergence and scenario termination events), the extent to which it is reasonable to account for the uncertain occurrence of FEPs in "normal evolution" scenarios, and the definition and utility of analysing "altered evolution" and "what if" scenarios.

For discussion:

1. What are the strengths and weaknesses of different methods for incorporation of scenario uncertainty in PA?
2. How can expert judgement methods to develop stylised scenarios be best developed and tested?
    a. What is the link to related activities in WP3.1 (scenario development)?
3. How can scenario probabilities be evaluated?

4.2.8 Task 2.2.D: Spatial variability

This task will evaluate approaches to treating uncertainties in PA calculations that arise from the spatial variability of facies, materials, and material properties inherent in the geosphere.

For discussion:

1. What are the strengths and weaknesses of different approaches to incorporate spatial variability in PA?
    a. What is the potential for applying geostatistical approaches in PA?
    b. How can different methods of upscaling be tested?
2. What is the link to related work in WP3.3 (source term upscaling) and WP4.2 (PA and geometric complexity)?

4.2.9 Task 2.2.E: Fully probabilistic assessment approach

This task will develop and test an integrated, fully probabilistic safety assessment approach incorporating scenario, model and parameter uncertainty.

For discussion:

1. What are the strengths and weaknesses of a fully probabilistic assessment approach?
2. Is the treatment of scenario, model and parameter uncertainties traceable to assessment results?
3. Can such an approach be adequately implemented in compartmental modelling software?
4. What is the link to related work in Task 2.1.C (Approaches to system PA)?

4.3 Way Forward

While RTDC2 addresses the bulk of topics of interest to PAMINA participants, some gaps in the work programme and in the WP1.2 review itself (this document) were identified in questionnaire responses and in comments made on the WP1.2 review draft report. Not all issues can necessarily be dealt with in PAMINA. However, there is flexibility built into the PAMINA programme via the requirement for annual reviews of, and revisions to, the work programme. This allows topics that come to prominence in the course of the project to be considered for inclusion in the work programme.

With respect to gaps in the WP1.2 review, as discussed in Section 2, the review had a limited scope, being designed primarily to feed into the WP1.2 March 2007 Brussels planning workshop and to gather information for the WP2.3 deliverable, without overlapping with specific additional reviews foreseen within the RTDC2 work programme (see Section 2.1). Gaps in this document will be filled in the final WP2.3 document to be produced in 2009. For example, a review of sensitivity analysis techniques will be carried out as part of Task 2.1.D in 2007/08, and summarised in the WP2.3 deliverable.

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Appendix A – Completed Questionnaire Responses

A1 Belgium – AVN

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	AVN
Responsible Person(s):	Vincent NYS
Date:	January 2007

1. *What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?*

After the publication of its SAFIR 2 report in 2002, ONDRAF/NIRAS decided to change the nature of its milestone reports for the high-level and long-lived radioactive waste management programme from a state-of-the-art report (SAFIR, 1989 and SAFIR 2, 2001) to a safety case type of report. The publication of the safety and feasibility case report 1 (SFC1) is planned for 2013. At that moment ONDRAF/NIRAS will officially submit its SFC1 to the institutional stakeholders (supervising minister and possibly the safety authorities). A national and/or international review of SFC1 after its submission to the authorities is possible.

The objective of the SFC 1 is to substantiate that, for a defined zone in the Boom Clay and for all currently foreseeable B&C waste streams considered in the Belgian program, the proposed disposal system:

1. has the capacity to ensure operational safety and passive long-term safety,
2. is judged to be feasible.

It should also substantiate that the proposed disposal system can be taken forward for further development and optimisation.

Our answers to the present questionnaire are based on the preliminary discussions between Belgian regulators and implementers about the development of the Safety and Feasibility Case 1 by ONDRAF/NIRAS. Due to the preliminary stage of development of the radioactive waste disposal programme, only some of the questions of the questionnaire have been selected and responded to.

2. *What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?*

Our approach is based on international guidance. Harmonization of basic requirements is directly or indirectly promoted by the working groups and the publications of international organizations such as the IAEA, OECD/NEA or ICRP.

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The recommendations laid down in the IAEA Safety Series documents play an important role in defining good practice and the IAEA "Joint Convention" (Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management) adds a binding commitment of the Convention Parties to certain basic safety requirements. The publications of the ICRP are influential in establishing common radiation protection standards. The various publications of OECD/NEA in the field of radioactive waste safety offer a good description of the state of the art, the different approaches currently followed and the degree of consensus nevertheless achieved in many fields.

Moreover, a draft document (untitled "*A minima requirements on argillaceous sedimentary formations*", ref. [4]) providing a guidance about sitting in argillaceous sedimentary formations for the geological disposal of radioactive waste has been developed. The document states fundamental requirements to be fulfilled by the host formation as well as a guidance on the role to be fulfilled by the environment of the disposal system.

These outcomes are derived from:

(1) the general regulatory framework applicable in Belgium;

(2) the safety approach and related principles of a geologic disposal of radioactive waste;

(3) the specific implementation constraints of repositories in argillaceous formations.

In the document emphasis has been put on three aspects: the fundamental principles (no quantitative "criteria"); the disposal system considered as a whole system; and the safety and feasibility aspects.

The document is foreseen as a living document to be updated by the regulators along the different steps of the siting process. Present potential applications of this guidance are the identification of (a) favourable zone(s) in argillaceous formations in Belgium.

Apart from the preceding considerations, as no specific regulations exist in Belgium for the disposal of radioactive waste, there are at the present time no official positions from the regulatory authorities concerning the handling of uncertainties or perturbing phenomena.

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3. How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.

In Belgium, the three following types of uncertainties are considered:

1. Uncertainties concerning potential future evolutions of the repository system (i.e. uncertainties about scenario) are addressed by requiring a well-structured procedure for the development of scenarios in order to ensure that a comprehensive set of reasonable scenarios will be considered. A scenario is not always meant to represent a plausible situation, but is designed to encompass various situations that are sufficiently similar. It is also possible to develop “What-if?” scenarios which might allow demonstrating robustness of certain repository components.

2. Uncertainties about models include simplification in the numerical models and numeric solutions. The conceptual, mathematical and numerical models (including codes) to be used in assessments should be developed according to established quality assurance procedures.

3. Uncertainties concerning parameters include both uncertainties concerning the exact value of a parameter at a fixed time and a certain place as well as uncertainties about extrapolation of this value for other times and places.

4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

It is the opinion of FANC/AVN experts that dividing overall periods into different time frames may be very valuable in carrying out safety assessments and in providing safety cases (although it should not be considered as a necessity). Furthermore, it permits to take account of the evolution of uncertainties through time.

When defining the different time frames to be considered, one has to cover all stages of the life of the repository and, in particular, the overall period(s) after closure, at least up to (and even beyond) the peak risk for each of the considered radionuclides. The reasons seen by FANC/AVN experts for dividing overall periods into time frames are to put in evidence, in the presentation of a safety case, that:

- Appropriate specific arguments (e.g. quantitative, qualitative) and safety indicators (e.g. dose, risk, radionuclides fluxes from the geosphere, …) are used in relation with the uncertainties for the time period considered;

- Overall performance of the disposal system is not unduly dependent on a

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single safety function and/or safety barrier especially when the potential hazard due to the repository is still high;

- The efforts of investigation envisaged for each time frame are proportional to the potential hazard of the repository. The investigations are relying on a reasonably well-established available knowledge.

The time frames could be defined, among others, on the following basis:

- The validity of prediction of the models;
- The states of the safety functions of the different components of the disposal system;
- The complexity and the possible coupling of physical and chemical processes. The existence of several consecutive processes (for instance in the early times after repository closure) may indeed be in favour of defining a finer division in time frames.

5. *How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.*

According to FANC/AVN experts it is possible, for some scenarios, to compensate the lack of knowledge by considering highly stylised and pessimistic hypotheses in the impact evaluations. In the view of the timescales it is the case for instance of the modelling of the biosphere for any types of scenarios. This aspect is being discussed at the present time between regulators and implementers in Belgium. A stylised approach is also used in the case of human intrusion scenarios.

Thus, examples of stylized approaches comprise the use of reference biospheres for future timescales and use of hypotheses about the constancy of human characteristics. It appears difficult to justify any other choices due to our lack of knowledge about the future.

As concerns integration of uncertainties within models, the way it is to be carried out highly depends on the level of uncertainties: the models and parameters that best reflect the physical reality as can be understood must be distinguished from those intended to provide a pessimistic representation (referred to as 'conservative' or 'penalizing or pessimistic', depending on the degree of pessimism). The model selection strategy is based on the following selection principles:

- in case of low uncertainty, the most scientifically supported model

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('phenomenological' model or **best estimate model**) is selected;

- in case of high uncertainty, a **conservative or pessimistic model or value** is selected;
- the most simple and robust models are privileged, as long as this choice does not lead to underestimating the impact.

The notion of 'low' or 'high' uncertainty inevitably entails a degree of subjectivity, even though in certain cases it may involve statistical considerations (dispersion of experimental values, level of confidence, etc.). The experts in charge of proposing the models and values discuss decisions regarding uncertainty on a case-by-case basis.

Finally, concerning uncertainties attached to models, it is generally preferred to use simpler, less-sophisticated models than more sophisticated ones that would imply higher uncertainties. This is drastically linked to the demonstrability of long-term safety in order to build the confidence through the different stages of the development programme.

6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of “fuzzy mathematics”; others)?*

Treatment of uncertainties is generally accomplished by using a combination of scenario variants, conceptual model variants, and parameter variations. It can be undertaken, among other ways, by the use of conventional deterministic or probabilistic uncertainty evaluation tools.

For uncertain parameters, either conservative choices are to be made or reasonable probability density distributions are to be derived. Probability distribution functions are based on collected data, on formal expert elicitations, or on a combination of these two approaches. Where there is no sound distribution for the creation of a probability distribution function, a bounding or conservative single value may be used. Sensitivity studies are performed to help understand the effects of uncertainty.

If the probability of a particular situation can be defined, if not always calculated, it can be much more difficult for a whole scenario. This is especially the case for “What if” scenarios which are not meant to represent a realistic situation but to test the robustness of the design.

Deterministic approach is the approach mainly considered up to now by ONDRAF/NIRAS in the development of its safety case. This approach is recognized as providing simplicity of interpretation and judgement of the results in the analysis

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of scenarios or assessment cases.

It is the opinion of FANC/AVN experts that both approaches (deterministic and probabilistic) are however valuable and should be considered when possible as complementary contributions to the safety case. Comparisons show the coherence between a deterministic and a probabilistic approach as long as they rely on the same underlying assumptions. However, the results of a probabilistic calculation, such as a distribution of expected dose, are difficult to use in a context where it is expected that the results of the calculation should be compared to a pre-defined threshold.

Therefore the regulator does not impose a probabilistic or a deterministic approach. Both approaches can be combined. However the regulator often has a preference for deterministic evaluations.

Five types of scenarios could be considered in the safety case (see document [1]) :

1. the reference evolution scenario(s) for the foreseeable evolution of the repository with respect to the most likely effects of certain or very probable events or phenomena;

2. The altered evolution scenarios taking into account the least likely effects of these events or phenomena and the consequences of events or phenomena that are not integrated into the reference scenario, as the likelihood of occurrence is lower;

3. The “beyond design limit” scenarios, result of very unlikely events, for which it appears that it is not reasonably possible to thwart the occurrence or the consequences. The consequences are closely linked to the strategy “concentration and containment” selected;

4. The imposed or conventional scenarios that are also known as “what if” scenarios, for which the occurrence of an event or random phenomenon is postulated although it seems possible to exclude it through design or the level of knowledge available;

5. And finally the scenarios relating to human intrusion.

7. How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.

Parameter uncertainty can be dealt with by using sensitivity and uncertainty analysis. In sensitivity analysis, the model input parameters are varied over sensible ranges to determine the effect of these variations on the model result. This increases our understanding of which parameters have to be determined with the greatest accuracy,

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and thus helps prioritise data collection requirements.

Sensitivity analysis provides a logical and verifiable method of optimizing the distribution of resources used to determine the most important parameters. It also indicates which parameters have to be included in the uncertainty analysis.

Uncertainty analysis gives a numerical estimate of how the uncertainty in the input parameters results in uncertainty in the model results (fluxes, doses, etc).

8. What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.

See answers to questions 5 and 6 above.

9. What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.

Considering the different phases throughout a disposal lifetime, uncertainties increase progressively with time, especially those associated to scenarios. For very long-term periods, when uncertainties become tremendously high, the importance set to the numerical results of the performance evaluations is reduced, and expert judgement is more commonly used in the safety assessments. While proceeding this way, it remains possible to cope with high levels of uncertainties.

Concerning the probability of occurrence of scenarios, simplified assumptions can also be made when uncertainties can not be easily estimated: for instance, in Belgium, a drastic assumption has been taken into account for “near-surface disposal”, as it is not possible to determine precisely the probability of occurrence of the “human intrusion scenario” in the very-long term, it has been decided to consider that this scenario has a probability of occurrence equal to the unity, which avoids further useless discussions about how likely such an event is or not. In case of geological disposal, this topic has not yet been formally discussed between operator and regulator.

Concerning uncertainties attached to parameters, a number of very useful information for evaluating them can be obtained from literature reviews, as many research programmes have been and still are commonly carried out throughout the world on high-level and long-lasting radioactive waste geological disposal. For less-studied subjects, R&D projects should also be initiated to increase knowledge when necessary.

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10. *What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?*

11. *How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.*

The Belgian programme is still at a preliminary stage of development. Hence, there is currently no particular example of how the management of uncertainties may influence the R&D programme.

However, there have already been exchanges of points of view between operator and regulator about the necessity of enhancing the study of the different types of uncertainties (uncertainties attached to parameters, models and scenarios) in the R&D programme. A particular highlight has been set on the necessity of developing an integrated approach when assessing uncertainties, which implies studying interdependances between the different components of the system.

12. *What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.*

One important advantage of a stepwise implementation process for a radioactive waste repository is that safety assessments are iteratively done and discussed with the regulator and the public at the different stages of development. The outcome of the assessment of uncertainties and especially the sensitivity analysis in an early stage is thus available to guide the preparation for the following stage of the process.

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13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

14. Any other comments?

15. What are the key references that support your response?

Our responses are based on preliminary discussions about Safety & Feasibility Case 1 (SFC1, to be published in 2013, see question 1 above) as well as on the following documents:

[1] "Geological Disposal of Radioactive Waste: Elements of a Safety Approach" (document developed within the general framework of the Franco-Belgian collaboration)

[2] Draft documents of a working group of European regulators ("European Pilot Group") about geological disposal of radioactive waste

[3] Answers to the "IGSC Timescales Questionnaire" (2005)

[4] "A minima requirements on argillaceous sedimentary formations", draft AVN document currently in discussion with FANC and ONDRAF/NIRAS, 31/12/2005.

[5] "Radiation Protection Recommendations as applied to the disposal of long-lived solid radioactive waste", Annals of the ICRP, ICRP Publication 81, Pergamon publisher, 2000.

Numerous international documents (IAEA, NEA, etc.)

A2 Belgium – ONDRAF/NIRAS and SCK/CEN

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	ONDRAF/NIRAS and SCK.CEN
Responsible Person(s):	Peter De Preter and Jan Marivoet
Date:	22/12/2006

1. *What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?*

With the publication of its SAFIR 2 (Safety Assessment and Feasibility Interim Report) in 2001 ONDRAF/NIRAS ended the second phase of methodological R&D regarding the deep disposal programme for high-level and long-lived waste. Since 2004 the programme entered the third methodological R&D phase. The prime aim of these methodological phases is to progressively establish if it is feasible, technically and financially, to design, build, operate and close a safe deep repository for this waste on the Belgian territory, without prejudging the actual disposal site. The R&D programme is mainly focussed on a reference argillaceous host formation (i.e. Boom Clay) and based on in situ data acquired in an underground research laboratory located in Mol/Dessel (NE Belgium) which is the reference site.

With the decision to install a moratorium on reprocessing of spent fuel in 1993 (confirmed in 1998) ONDRAF/NIRAS was asked to study both the options of disposal of reprocessing waste and of direct disposal of spent fuel.

It should be noted that neither deep disposal nor argillaceous formation(s) have yet been formally agreed upon or designated by the Belgian Government as the long term management solution for high-level and long-lived waste. Decision-in-principle to go for disposal in argillaceous settings will be requested on the basis of a national waste management plan supported by a strategic environmental assessment to be elaborated by ONDRAF/NIRAS in the next few years (2007-2010).

The next technical and scientific milestone of the deep disposal programme will be the publication and submission to the supervising Minister and the safety authorities of the Safety and Feasibility Case 1 (SFC 1) by 2013 which should lead to a "go for siting decision".

2. *What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?*

No disposal specific regulatory standards exist at the moment in Belgium, and the regulatory body (the Federal Agency for Nuclear Control) is currently defining protection criteria for disposal and is developing regulatory guidance.

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3. *How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.*

Uncertainties are classified in the categories "scenario uncertainty", "model uncertainty", "parameter uncertainty". We also make a distinction between poor knowledge (lack of data) and variability in space and time, but this distinction is not yet systematically introduced in the programme.

Examples

- Scenarios:

1) altered evolution scenarios themselves can already be considered as an uncertainty in the evolution;

2) variants of a scenario: in expected evolution scenario: evolution of climate: Milankovitch or greenhouse;

- Models: transport of actinides in clay: complexation by organics (fulvic acids) vs. low solubility and sorption on clay minerals;

- Parameters: for essential parameters (e.g. solubilities and transport in clay) parameter distributions have been estimated.

4. *How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.*

- Scenarios: separate simulations of the variants of a scenario are carried out;

- Models: simulations are done for both models and results are compared to estimate the potential impact on the output variable;

- Parameters: both stochastic (Monte Carlo simulations) and deterministic, depending on the problem.

5. *How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.*

For most issues there is not enough knowledge to quantify in a rigorous way the uncertainties.

E.g. transport parameter values (sorption coefficients, solubility limits, …) : it is not possible to identify pdfs by applying statistical techniques; therefore, most

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uncertainties are described by a log-uniform distribution for which a best estimate value and an uncertainty factor were estimated.

Conservative parameter values are often used to avoid the problem in quantifying uncertainty (see also answer to question 6).

6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?*

A distinction is being made between "process modelling" and more detailed scopings on the one hand and compliance assessments on the other hand. The former assessments are part of the assessment basis and aim at an adequate system understanding, based on a more realistic modelling approach where possible and appropriate. The latter are the more simplified conservative assessments, which are dealt with in the quantitative safety and performance assessment part of the safety case.

Deterministic and probabilistic calculations are seen as complementary and both approaches are adopted. The deterministic approach presents advantages when interpreting the results in terms of compliance and when presenting the results to various stakeholders. Probabilistic calculations are a tool for evaluating some type of uncertainties (combined parameter value uncertainty) and sensitivities.

7. *How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.*

With sensitivity analyses we are trying to determine which elements (e.g. input variables) have the largest contribution to the uncertainty in the output variable (e.g. dose).

With uncertainty analysis we try to quantify the uncertainty in the considered output variable.

In mathematical terms: sensitivity analyses look at the relation between Y (output variable) and X (input variables), whereas uncertainty analysis considers only Y.

8. *What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.*

The systematic identification of uncertainties as a central element of a safety case is a first and most important way to provide confidence.

In compliance assessments conservative assumptions are made to take into account

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the identified uncertainties and a safety case should make these conservatisms "visible". For the most important contributors to safety (e.g. the geological barrier ensuring very low radionuclide migration once the radionuclides are released from the EBS) it is argued that an adequate understanding is available. The remaining uncertainties for these major contributors to safety (e.g. from a critical radionuclide like Se the radionuclide speciation and the effects on the migration parameters) are treated by making conservative assumptions or by making assessments for the possible cases.

The effects of these remaining uncertainties are assessed in order to evaluate if they can jeopardize the safety of the system.

9. What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.

Design options, introduction of conservatism.

Design option: the use of a long-lived (a few thousand years) container avoids that the uncertainties associated with temperature evolution and parameter values applicable at elevated temperatures (radionuclide releases from the waste form and radionuclide migration) have to be taken into account in the analysis of the expected evolution scenario.

Conservatism: conservatism is already applied during the data collection; for parameters for which there is little information available, conservative parameter values are used.

Another conservative approach is the introduction of the robust concept: components that might, even significantly, contribute to the performance of the repository system are not considered in the evaluations, e.g. sorption of radionuclides on the iron(hydr)oxides that were formed in the near field during corrosion of the container.

10. What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?

For the vitrified HLW and spent fuel Se-79 is the most critical radionuclide. Uncertainties on its speciation in the waste form and during migration in the Boom Clay, and, consequently on its migration behaviour are remaining and important for assessing the safety. Biosphere conversion factors for Se-79 are another important remaining uncertainty.

Critical radionuclide inventories (Se-79, I-129, Sn-126, …) for HLW and spent fuel (for different burn-ups, UOx and MOX) are also an important source of uncertainties

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requiring further characterisation and calculation work.

The EBS behaviour and performance (engineered containment, radionuclide release rates for vitrified HLW and spent fuel in the supercontainer design) are also a source of uncertainties requiring further work.

11. How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.

The uncertainty analyses in formal SA calculations or in scoping assessments aim to identify the most important uncertainties for safety. In a second step one evaluates the need and possibility(y)(ies) to reduce the important uncertainties. This is to a large extent expert judgment and is done in an integrated manner, i.e. by involving “design”, “system understanding” and “safety” people.

ONDRAF/NIRAS is developing a comprehensive methodology of safety and feasibility statements to systematically evaluate the need for further R&D&D work on specific issues in view of preparing the next safety case (2013). This process is fed with scoping PA and SA calculations. Formal SA calculations are planned in the final phase of safety case development.

12. What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.

In discussions with stakeholders other than the regulator the question of uncertainties is often related to the question “have you considered or taken into account this or that ?” (e.g. early failure mechanisms, seismic events perturbing the host rock, …).

The time scales are definitely an issue in discussions with these stakeholders and a multiple lines of reasoning approach is required to deal with these time frames (different safety arguments for the different time frames).

In view of the preparation of a licence application for the surface disposal of short-lived waste, the interaction with the regulator is ongoing, and the way to deal with uncertainties is one of the issues.

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13. *With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.*

Main gaps:

Classified: +/- OK; (1) scenarios, models, parameters; (2) poor knowledge, variability in space and time.

Managed: most uncertainties can be managed individually (pdfs, geo-statistics, alternative models, scenario variants, conservatism, etc.); more difficult issues are how to describe the increase of uncertainty with time.

Analysed: the individual uncertainties can be analysed; however, **the main remaining problem is how to combine all of them in a coherent and consistent way;** the traceability of the treatment of uncertainty remains a difficult issue.

Conclusions for future work: determination of research priorities by combining identified open questions and results of sensitivity analyses: +/-OK

Communication: remains difficult.

14. *Any other comments?*

15. *What are the key references that support your response?*

- SAFIR 2
- Ongoing work in view of the safety case 2013 (safety and feasibility case 1)

A3 Canada - OPG

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	Ontario Power Generation (OPG)
Responsible Person(s):	Theo Kempe / Paul Gierszewski
Date:	8 December, 2006

1. What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?

See INTESC response I.2, with the following update (ref. attached paper submitted to NEA Symposium):

- The Canadian Nuclear Safety Commission (CNSC) has issued a draft scoping document for the Environmental Assessment (EA) required prior to licensing, and an associated CNSC public hearing took place on October 23, 2006 in Kincardine;
- CNSC are expected to make a recommendation on EA 'track' (Comprehensive Study or Panel) to the Minister of the Environment, followed by the Minister's decision.
- The first phase of detailed site characterization is under way. A 2-D seismic survey was carried out in October 2006, and drilling of the first two deep boreholes started at the end of 2006. OPG will consult with CNSC staff with regards to the adequacy of the subsurface characterization data to support EA preparation in 2009.

2. What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?

Requirements are given in the Nuclear Safety and Control Act and regulations. Specific regulatory expectations are given in a CNSC Policy (P-290) and Regulatory Guide (G-320; draft issued for public comment April 2005; expected to be published by the end of 2006). The guide gives CNSC's expectations and compliance is not mandatory. However, similar expectations are given in the EA scoping document, which must be followed in the EA review.

The NSCA and regulations, also P-290 and G-320 can be found on the CNSC's web site, at

http://www.nuclearsafety.gc.ca/eng/regulatory_information/documents/index.cfm

Material relevant to uncertainty is in draft G-320, Sections 7.2, 7.5, 7.8, 8.0, and 9.0 (these sections may change in the final).

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Organisation(s):	Ontario Power Generation (OPG)
Responsible Person(s):	Theo Kempe / Paul Gierszewski
Date:	8 December, 2006

3. How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.

Following guidance given in IAEA documents, uncertainty in assessments is recognised as:

• uncertainty in the evolution of the disposal system over the timescales of interest (scenario uncertainty);

• uncertainty in the conceptual, mathematical and computer models used to simulate the behaviour and evolution of the disposal system (e.g. owing to the inability of models to represent the system completely, approximations used in solving the model equations, and coding errors); and

• uncertainty in the data and parameters used as inputs in the modelling.

In addition, IAEA suggests that a further type of uncertainty, subjective uncertainty (uncertainty due to reliance on expert judgement), is also linked with the above sources of uncertainty.

See also INTESC response II.12.

4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

See INTESC responses II.12, II.19, II.20, II.22 and III.3.

5. How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.

The Safety Case emphasises the geosphere and the studies carried out to date indicate that favourable geological and hydrogeological conditions exist at the Bruce site, as summarised in Section 8 of the attached paper to the NEA Safety Case Symposium. The validity or otherwise of these assumed favourable characteristics will be tested in ongoing site characterization work and work aimed at developing a geosynthesis, or integrated geoscientific understanding of the past, present and future evolution of the Bruce site.

The main uncertainties relate to characteristics of the geosphere, and are expected to be resolved to a level acceptable to the regulator by this ongoing work. Current safety assessment work takes account of these uncertainties by analyzing several scenarios, e.g. a what-if case which assumes unfavourable features such as advective flow in certain strata. The safety assessment will incorporate the results of ongoing

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site characterization and engineering work in an iterative manner.

See also INTESC response IV.7.

6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?*

Analyses are primarily planned to use realistic assumptions however certain conservative assumptions are inevitable for deterministic calculations where there is uncertainty. It is planned that interpretation of results and application of criteria will take account of the features of the analysis. Overall, our approach could be described as deterministic complemented by probabilistic, and a balance of simplified and complex modelling.

See also INTESC responses II.16 and II.22.

7. *How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.*

See INTESC responses II.12, II.17 and II.18.

8. *What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.*

See INTESC responses II.9, IV.10 and IV.11. These arguments are also summarized in Section 4 and 8 of the attached paper submitted to the NEA Safety Case Symposium.

9. *What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.*

See previous responses.

The uncertainty in the future evolution of the site is to be addressed using a transparent and comprehensive scenario development and justification methodology, which will ensure that an appropriate range of potential futures is considered. Physical variability and individual parameter uncertainty will be treated using sensitivity and uncertainty analyses, whilst conceptual model uncertainties will be treated using alternative conceptual representations of the system. The uncertainties related to computer codes will be reduced through the use of appropriately verified and validated computer codes (selected considering the available data and the calculation end points). Subjective uncertainties will be managed by using a systematic and transparent approach, consistent with the ISAM methodology, which

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allows subjective judgements to be documented, justified and quantified (as far as possible).

10. What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?

In accordance with G-320 and the EA scoping document (see response to Q. 2), acceptance criteria are to be proposed and discussed with the regulator, CNSC.

It is expected that uncertainties can be managed, primarily through the stepwise and iterative approach adopted. Presentation of the overall Safety Case will be an important factor.

11. How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.

See INTESC response II.2.

12. What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.

Key elements in presentation of the Safety Case for the DGR include emphasis on simple robust arguments supported by multiple lines of reasoning including more detailed calculations, and consistency with international practice.

See also INTESC responses VI.2.

13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

At this stage of the DGR project gaps in understanding have not been identified other than those identified to be addressed in planned work. This will be explored in ongoing interaction with the regulator, CNSC.

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Responsible Person(s):	Theo Kempe / Paul Gierszewski
Date:	8 December, 2006

14. Any other comments?

Technical note: For parameter sensitivity analyses, we are using a numerical technique based on Iterated Fractional Factorial Design (IFFD) and implemented in a pair of codes SABERS/SAMPLE. A description of the approach is given in a paper by T. Melnyk et al. (Identification of important parameters in large safety assessment system models, IHLRWM conference, Las Vegas, 2006; copy attached).

15. What are the key references that support your response?

See the references given in INTESC response I.4. These references are available on the OPG DGR website, at http://opg.com/power/nuclear/waste/dgr.asp (Please advise if paper copies are needed.)

Golder 2003 is under the "additional reports" link
Golder 2004 is under "Independent Assessment Study"
INTERA 2006 is under "Site Characterization Plan"
Parsons 2004 is under "Conceptual Design", and
Quintessa 2003 is under the "additional reports" link

Mazurek 2004 can be found on the website of the Canadian organization responsible for the study of long-term management of used fuel, the NWMO, at

http://www.nwmo.ca/Default.aspx?DN=713,237,199,20,1,Documents

The paper referred to in the responses, submitted to the NEA January 2007 Symposium on the Safety Case, is attached.

The OPG response to the NEA INTESC questionnaire is attached.

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Responsible Person(s):	Theo Kempe / Paul Gierszewski
Date:	8 December, 2006

Paper by Melnyk et al. is attached

A4 Czech Republic - NRI

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	NRI Rez, Czech Republic
Responsible Person(s):	Ales Laciok + Jiri Landa
Date:	March 2007

1. What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?

Initial stage (deep geological repository) – preliminary analyses focused mainly on constructability aspects and general environmental impacts has been performed so far. Comprehensive safety assessment has not been carried out so far (only particular analyses has been performed – near-field processes, biosphere processes,..). Six selected sites were evaluated in desk top study complemented by airborne geophysical reconnaissance in previous years (assessment of available geological information, clash of interests, comparison with exclusion and limiting criteria,..), geological survey was interrupted after protests of local inhabitants 3 years ago.

2. What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?

Regulatory requirements are specified in the Decree of SONS no. 307/2002 Coll., on radiation protection. The relevant part is Par. 52:

"The fulfilment of the requirements for radiation protection in radioactive waste disposal shall be demonstrated by safety analyses of potential hazards of radioactive waste disposal. Based on the knowledge of the site where the repository shall be built, safety analyses shall demonstrably and plausibly assess the potential risks during the operating period as well as during the period after the repository is closed. Based on the safety analyses, acceptance criteria for radioactive waste disposal shall be determined."

SONS = State Office for Nuclear Safety (regulatory body in the area of nuclear safety and radiation protection).

3. How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.

No specific rules for classification of uncertainties in repository safety evaluations have been established in SONS decrees or other binding documents so far.

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Organisation(s):	NRI Rez, Czech Republic
Responsible Person(s):	Ales Laciok + Jiri Landa
Date:	March 2007

4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

Quantitative PA – appropriate tools used in other branches.

Wider safety case – referencing to quantitative PA results, rather qualitative and semi-quantitative approaches would be used, comparisons, reasoning by analogy,..

5. How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.

It is probably subjective perception/view of scientists reflecting their professionalism, level of knowledge and experience. In reality it is a matter of compromise – peer reviews, clarification of views of professionals from different fields, evaluators, other stakeholders, etc.

6. What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?

Such questions are correlated with the stage of development of repository. Due to the initial stage of deep disposal programme in the Czech Republic, the total performance assessment would be based on simplified, but reliable models (rather deterministic than probabilistic). Reliability (enveloping of impacts, safety margins) could be based on more complex models of main processes (and their coupling), incorporating evaluation of uncertainties at this level of modelling.

In consequent stages, role and use of probabilistic approaches will be considered.

7. How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.

It is recommendable to follow standard scientific literature and relevant references.

8. What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.

In the Czech disposal programme, natural analogues are used for qualitative argumentation concerning confidence in character and intensity of events and processes.

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Organisation(s):	NRI Rez, Czech Republic
Responsible Person(s):	Ales Laciok + Jiri Landa
Date:	March 2007

9. What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.

QA is integral part of deep disposal programme, but QA procedures alone cannot substitute evaluation of uncertainties.

10. What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?

Unclear context and not properly defined limits of safety analysis, undefined purpose of use of probabilistic approaches and non-coherent and biased argumentation could jeopardise expected results.

11. How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.

Rather intuitive actions and following of international activities are main drivers of research priorities. Uncertainties are used only in qualitative ways if any.

12. What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.

Possibility to comprehend the presented results and ways of derivation of results (appropriate level of simplification, graphical forms rather than only numerics) and argumentation by reasonable similarities/analogs. Different approaches for different forums are needed!!

13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

Role of uncertainty and sensitivity analysis has to be clearly defined before starting complex calculations and their interpretation as a part of the safety case.

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Organisation(s):	NRI Rez, Czech Republic
Responsible Person(s):	Ales Laciok + Jiri Landa
Date:	March 2007

14. Any other comments?	
15. What are the key references that support your response?	
RAWRA (Czech Radioactive Waste Repository Authority) http://www.proe.cz/surao2/index.php?Lang=EN&p SONS (State Office for Nuclear Safety) http://www.sujb.cz/?r_id=26	

A5 Finland - POSIVA

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	Posiva
Responsible Person(s):	Marjut Vähänen
Date:	31.1.2007

1. What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?

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.

2. What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?

Generally, management of uncertainty shall be an integrated element in all parts of the Safety Case. The management of uncertainty shall correspond to the stage of the

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	Posiva
Responsible Person(s):	Marjut Vähänen
Date:	31.1.2007

repository programme.

In accordance with the Government Decision on the safety of the disposal of spent nuclear fuel (Government of Finland 1999), a safety assessment shall include uncertainty and sensitivity analyses and complementary discussions of such phenomena and events which cannot be assessed quantitatively. 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. 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. Employing of relatively simple deterministic models facilitates comprehensive uncertainty analyses based on systematic combinations of the best-estimate and conservative parameter values. In addition, uncertainties are covered and the significance of barrier functions are illustrated by means of bounding and "what if" analyses.

3. How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.

Concerning the release from spent fuel assemblies, near-field transport and geosphere transport, the uncertainties are more related to limited knowledge than to random spatial or temporal variability. Therefore, their modelling in the near future may be based on deterministic parameter values.

In report Posiva 97-11 the classification of FEPs in Finnish safety assessments have been presented. In principal the approach has been the same in TILA-99 two years later. Examples:

- Post glacial faulting: Treatment by separate scenario.
- Uncertainties in solubility limits: Treatment by separate calculation case with more conservative data parameters.

Gas expels water from canister: Treatment by separate scenario or model. What's the difference between model and scenario? The conceptual model differs from base case but the same computer model REPCOMM has been used.

4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

Parameter uncertainty is primarily analysed by defining bounding analyses and sensitivity cases. In selecting the parameter values from databases (e.g. instant release fractions, solubility), the recommendation is to use the best estimate and conservative values; for certain important parameters in the biosphere assessment, a

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
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stochastic approach might be used if appropriate well-established probability density functions can be derived.

The applied parameter values, the data the values are based on and the reasoning behind the selection of a given value should be reported. In cases when just one parameter value is used in modelling reporting should include discussion on the effect of the parameter uncertainty on the results. Furthermore assessing the consistency of modelling results against other relevant models and any experimental or field observations can be done.

Structural approach, including iterative analyses, are being developed to handle parameter sensitivities and uncertainties.

5. *How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.*

Considering site description, preliminary measures to discuss sufficiency of data have been established so that there exists common understanding adequacy of site description (i.e. processes and relevant data) and the further work needed. Currently, the site description is not unambiguous.

Uncertainties with respect to evolution related scenarios can't currently be circumvented by other means than combination of deterministic analysis and complementary (somewhat) realistic bounding analyses.

Estimates of unexpected events when radionuclides are released and their consecutive concentrations in various media together with their radiological effects bear more comprehensive uncertainties. It seems that radionuclide transport related uncertainties are due to the current perception of site hydrogeology and how it is parameterised. Therefore, the only means to master these uncertainties is to use quasi-stochastic estimates i.e. to assess the robustness using several sets of assumptions and parameters.

6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?*

See answer to question number 3 concerning the release from spent fuel assemblies, near-field transport and geosphere transport.

Regarding the biosphere, a realistic approach is taken for the description of the site, and the description of the evolution of the site will be based on realism-oriented modelling. For the radionuclide transport of multiple nuclides through several

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connected ecosystems significant conservative assumptions are needed.

7. *How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.*

This is a philosophical question. E.g. changes in solubility limits, source term or canister failure time may be considered as sensitivity analyses in TILA-99. Gas expels water or post glacial faulting scenarios may be considered as uncertainty analyses.

8. *What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.*

Properly sealed copper canister in KBS-3 concept is inherently chemically resistant and with cast-iron insert mechanically resistant and therefore canister is inherently integrated thus providing long-term isolation.

Canister integrity is supported by buffer material enclosing it. Buffer eliminates or attenuates the influences of near-field conditions to canister i.e. decouples these effects either totally or with sufficiently long reaction times so that the effect of disturbance in conditions faced by buffer remains sufficiently small.

In case canister is groundwater flows into canister e.g. through a defect in sealing, solubility of fuel matrix is negligible and even when being leached, the pressure inside the canister remains considerably small when compared to the pressure at buffer or the pressure at depth of the repository. Also the retardation parameters of majority of critical nuclides is well known and proven.

9. *What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.*

For the biosphere assessment, a multi-dimensional uncertainty analysis approach has been outlined to be taken into use in largest extent practically achievable. The approach combines traditional uncertainty and sensitivity analysis with methodologies for quantifying non-numerical uncertainties, such as pedigree analysis for the evaluation of uncertainties in the knowledge base. The methodology might be extended also to other areas of the safety case after more experience on the practical implementation has been gained.

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Date:	31.1.2007

10. *What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?*

Interaction of the intended buffer and backfill material with the groundwater composition prevailing at specific times. An additional uncertainty relates to the interaction effects of stray materials used in constructing the repository and engineering barrier materials (e.g. cement used in groundwater inflow control into excavated volumes and its interaction with clays intended for buffer and backfill.

11. How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.

The results can be used to identify processes and parameters that have a combination of high impact on the safety assessment end-results (such as doses to man and other biota) and epistemic uncertainties that could be further reduced. This can provide valuable input for where the focus of future work should be, especially monitoring programs and R&D activities. In analogy, uncertainty analysis results are valuable to identify processes and parameters less significant for the safety assessment end-results, which is also important when optimising the resources.

Construction methods and materials are being optimised with respect to their potential implications on the long-term performance of the repository. The greater the uncertainties are, the more conservative (= time and labour consuming) design and construction methods are used.

12. What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.

Transparent and continuous discussion.

13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

How to classify the relative importance of new uncertainties appearing once in a while.

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Organisation(s):	Posiva
Responsible Person(s):	Marjut Vähänen
Date:	31.1.2007

14. Any other comments?

15. What are the key references that support your response?

Vieno T., Ikonen A.T.K. (2005). Plan for Safety Case of spent fuel repository at Olkiluoto. POSIVA 2005-11.

Nuclear Waste Management of the Olkiluoto and Loviisa Power Plants: Programme for Research, Development and Technical Design for 2007–2009. TKS 2006.

Ikonen, A.T.K. Posiva Biosphere Assessment: Revised Structure and Status 2006. POSIVA 2006-07.

A6 France - ANDRA

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	ANDRA
~~Responsible Person~~(s):	Contact persons for PAMINA WP1.1 group: Lise GRIFFAULT and Sylvie VOINIS
Date:	09 February 2007

1. *What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?*

INTESC I.2 Describe briefly the status of your national programme (the programme may, for example, be at the stage of generic feasibility studies, or be in the process of selecting a site or sites for characterisation from the surface or from underground), including your programme constraints (see table A.3 for examples).

The French Waste Act dated 30th December 1991 initiated a research programme to define methods for the long-term management of HLLL waste [2]. It has entrusted Andra, the French National Radioactive Waste Management Agency, with the task of assessing the feasibility of deep geological disposal of this waste, and of producing a report after 15 years of investigations, including (i) a feasibility-assessment report on clay formations namely the dossier 2005 Argile based notably on the work conducted on the site of the Meuse/Haute-Marne Underground Laboratory and in foreign laboratories; and (ii) a report concerning the advantages of granite rocks based on the available bibliography on French granites and on the investigations carried out by Andra under research partnerships with foreign laboratories.

2. *What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?*

3. *How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.*

INTESC II.16 If conservative model assumptions and pessimistic parameter values are used for the treatment of some uncertainties, what rationale is used for the selection of uncertainties to be treated in this manner?

Depending on the knowledge acquired for each phenomenon or material, four different types of models might be available at a given stage of the project development:

- A so called "*modèle phénoménologique*", or "best estimate model", is either, the model that is based on the most comprehensive understanding of

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Organisation(s):	ANDRA
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Date:	09 February 2007

the phenomenon to be modelled, and whose ability to account for direct or indirect measurements has been confirmed, or in comparison with the 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. Examples of the former include basic physical models (Coulomb's law, etc.) and mechanistic models representing Fick's law or Darcy's law for example. Examples of the latter include all models subject to a broad-reaching experimental validation and/or a solid international consensus among experts in the field.

- A so called "*modèle conservatif*", or "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's impact, compared with the results that would be obtained by taking into consideration all the relevant phenomena in the chosen parameter variation range. For example, selecting a transport model that ignores chemical retention could, in situations where retention has a potentially significant effect, be deemed "conservative".

- A so called "*modèle pénalisant*", or "pessimistic model", designates a model that is not based on phenomenological understanding, however empirical, but that definitely overestimates the repository's impact. For example, making an assumption that waste packages immediately release radionuclides is, except in special cases, a pessimistic choice.

- Finally, an "alternative" model stands for a model that can't be classified according to this three items list but offers a different perspective. Examples might include models that don't have an unequivocal effect on the impact, or models that appear more comprehensive than the selected reference model but have been less thoroughly validated.

A parallel classification is defined as regards parameter values:

- A "phenomenological" value is considered to offer the best match between the model's results and the measured results. This choice must be supported by detailed arguments which may include a representative number of measurements, a physical reasoning that demonstrates that the chosen value is the most representative based on reliable data, or a judgement by recognised experts unambiguously designating it as the most appropriate value for the study context.

- The "conservative" value is chosen among those generated by the studies and measurements which give a calculated impact in a range of high values, all other parameters being equal. In the simplest case, where the impact

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increases (or conversely, decreases) as the value of the parameter increases, a value in the highest (or lowest) range of available values. "Conservative" values cannot be defined if the variations in impact are not monotonic with changes in the parameter.

- A "pessimistic" value is one that is not based on a state of phenomenological understanding, but is chosen by convention as definitely yielding an impact greater than the impact that would be calculated using possible values. Such values can represent physical limits. A pessimistic value can also be equal to the conservative value plus (or minus, where applicable) an appropriate safety factor that places it significantly beyond the range of measured values. A value cannot be described as "pessimistic" if the variation in impact in response to a variation in a parameter cannot be characterised.

- In order to explore the possible parameter variation ranges, one or more so-called "alternative" values can be suggested as a means of investigating the effect of contrasting values.

4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

INTESC II.12 Give a brief description of your strategy for the management and treatment of uncertainty in your assessments, including any scheme that is adopted for different timescales or for the categorisation of uncertainties (e.g. as scenario, model and data uncertainties). (Note: your response may overlap with that for the following questions; please use forward and backward referencing where appropriate)

The assessment of a repository feasibility assumes that a sufficient knowledge of the behaviour of the repository components has been acquired, in particular, thanks to the composition of a large corpus of scientific knowledge and development of a repository architecture down to a sufficient level of detail, and taking into account unavoidable uncertainties when considering evolution over hundred of thousand of years. Over such timescales, no feed back is available other than by means of natural and archaeological analogues. This does not mean, however, that these residual uncertainties related to the long durations, specific to the dossier, cannot be managed with a sufficient degree of confidence:

- Provisions are taken with regards to the repository conditions which would allow overcoming uncertainty consequences: choice of a very stable geological medium hardly affected since its deposition (155 million years ago), compartmentalisation of the repository into zones to prevent

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interactions between various kinds of waste, use of simple materials whose behaviour is well-known.

- In addition, to ensure the control of uncertainties, safety is integrated upstream the design phase in order to orient the choices toward the most robust solutions with respect to a possible lack of knowledge.

Finally, uncertainties are systematically investigated, and taken into account in the safety assessment. Their potential effects are examined, particularly in qualitative safety analyses

To conduct that investigation, Andra implemented three complementary approaches to synthesise the knowledge, describe the repository evolution and manage the uncertainties:

- Knowledge reference documents were made up in order to provide a complete view of the scientific understanding on the following studied components: geological medium, engineered materials, packages, etc. They describe indeed 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.

- 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, 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 APSS/PARS led to a list of uncertainties (on phenomenology, models, data, component characteristics...).

The uncertainties are not of the same kind depending on the time periods, components or parts of the repository and its environment. The various timescales considered are integrated in the safety analysis within the scope of the safety functions; the performance assessment and the analysis of the uncertainties (see details in questions II.21).

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5. How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.

INTESC II.14 What are the criteria or procedures whereby some FEPs or parameter combinations are excluded from detailed consideration and others are included (including e.g. the use of expert elicitation and peer review)?

A qualitative safety analysis (QSA) methodology was developed for detailed consideration of FEPs in the Dossier 2005 Argile [3]:

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.

The first objective is to identify whether the uncertainties are correctly covered by the SEN, either in its reference version, or in the sensitivity studies considered. If some of the uncertainties are not, it must be confirmed that they would have little impact on the repository, or that they refer to very unlikely situations.

As a second stage, if the uncertainty is not covered by the SEN, the function(s) and component(s) that could be affected must be identified. A systematic component-by-component analysis is used in particular to identify the shared causes of the loss of several functions: for example, an incorrect assessment of the long-term behaviour of a material can affect all the components that contain it, even though these could have

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different functions. The qualitative safety analysis provides an assessment of the degree of independence of safety functions, by identifying the possible uncertainties affecting several functions.

The effect of taking each uncertainty into account is described (i.e. the behaviour of the repository if the worst-case value of the parameter in question was the actual value, or if the risk envisaged actually occurred), in terms of the repository's evolution. This is done on the basis of the functions that are likely to be lost. For example, if a series of uncertainties can call into question the function « regulate the pH in the vitrified wastes cells », the corresponding situation is described, i.e. the effects of an uncontrolled increase in pH. If the design can cancel this effect, or if this is taken into account in the SEN or in its sensitivity calculations, the analysis stops at this stage. If a safety function can be affected and the evolution of the repository could start to diverge from normal, with a possible impact on other components, this effect is then specifically identified.

The qualitative safety analysis was conducted by Andra engineers who were not involved in writing the scientific documents. In this way, the safety analysis is given a certain degree of independence, since the people in charge of analysing the uncertainties and the possible altered situations (the safety engineers) are not the same as those who established the phenomenological plan for normal evolution. Four altered evolution scenarios have been adopted by Andra : the seals failure scenario, the package failure scenario, the bore-hole scenario and a severely degraded scenario which radically lower performances of safety functions. Specific qualitative analyses of external events were also conducted.

6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?*

INTESC II.13 Do you adopt a probabilistic and/or deterministic approach for the analysis of scenarios or assessment cases and what is the rationale behind your choice?

In accordance with the French Safety Rule RFS.III.2.f, the kind of approach, which has been adopted for the safety analysis, is mainly deterministic. This is implemented at two different stages; first for the definition of the SEN (normal evolution scenario) and SEA (altered evolution scenario), and then during the scenarios modelling computation and analysis itself.

The normal evolution scenario is defined as a set of evolutions that appear probable enough to be treated as normal, rather than as a single linear scenario. Therefore, in

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addition to the deterministic elements, it also comprises some events defined with a high occurrence probability. For instance, the welding of the caps of the canisters is a very accurately monitored process, but it has been considered that a certain percentage of faulty quality checks would be unavoidable. Then, considering the present nuclear industry standards, a deterministic assumption of one canister's default per each waste type was considered within the SEN.

As regards the modelling and computation of the scenarios, the approach is also mainly deterministic. 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 case a limited number. (See answers in III.5 for more details about the models and parameters selection and use.)

7. *How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.*

INTESC II.17 What kinds of analyses are carried out to explore parameter sensitivity and the impact of uncertainties in parameter values?

The SEN and SEA and their sensitivity studies form a non-dissociable whole.

The scenario is made up of a series of calculation cases. As an example in the case of the Normal Evolution Scenario is a « reference calculation » that sets out Andra's current knowledge of the repository's foreseeable evolution, in an approach that considers both the fruits of scientific research and the safety strategy. The purpose of this calculation is to assess factors that would increase the impact of creating a repository. To this end, it includes a series of parameters and models, chosen on the best available scientific knowledge. It incorporates a degree of conservatism that varies according to the uncertainties, being less conservative where the parameters or models have been validated in detail, and being more conservative where substantial questions remain outstanding. In addition, a series of single- or multi-parameter sensitivity analyses that set out of rank the parameters and models by determining the ones that, if they were to vary, would have the greatest consequences for the overall assessment.

8. *What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.*

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9. What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.

See question 5 for QSA Methodology.

Also note QA:

INTESC II.6 How does the quality assurance (QA) plan cover the different elements of the safety case? Which components of a safety case are covered by a QA?

According to the principles defined in the ISO 9001 standard, Andra has defined processes regrouping activities, which contribute to the same finality and are oriented toward a customer's satisfaction. The definition of a process allows transversally looking at the units' activities and defining the actions of improvement related to the relevance, effectiveness and efficiency of the process with respect to its objectives. The performance of the processes is reported through indicators. The processes are assessed in one or two annual reviews during which the results obtained are examined. They are linked to the notion of « continuous progress », which is essential in the quality field. A progress action does not necessarily indicate an insufficiency in the process, but rather an opportunity to improve its operation. This organisation allowed inciting engineers in charge of the studies to identify possible ways of improvement. They involved especially the management of the project's configuration and the control of the scientific data. A general document management procedure is related to project management (on the establishment of management plans, controlling reviews, etc.). Additionally, according to adequate procedures, at each key step of the establishing of the safety case (design options, scenarios, quantification of scenarios and related data sets), internal reviews are implemented and recorded in order to get experts' views and make decisions.

10. What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?

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11. How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.

The management of uncertainties and open issues in future project stages

INTESC IV.7 Have uncertainties, and assessment methodology, open siting and design issues been identified that must be addressed in future project stages? If yes, which ones? How are they identified and prioritized?

The dossier 2005 Argile, presents a few lines of progress from the conclusions of the safety analysis with a view to possible future work for instance in its last chapter of the safety tome, without pre-empting the decisions which will be taken in 2006 regarding research work on the deep geological repository. These focus on several areas: consolidation of the data acquired within the Meuse/Haute-Marne laboratory, full-scale technological tests to support more detailed engineering studies, work to explore the transposition zone on a larger scale and a more precise evaluation of the safety through more thorough knowledge of the phenomenology. On this final point, Andra stressed that the representation of the processes and their inclusion in the safety assessment of Dossier 2005 involves simplified, conservative models in certain cases and that it would be important in a later phase to represent them in a more precise manner in order to increase the confidence that can be placed in the assessments. In chapter related to lessons learnt, it was mentioned that the construction of a working programme for the years post-2005 depends on decisions from the public authority; on the other, it depends in part on the result of the assessment of the dossier and the recommendations arising from it.

Dossier 2005 also marks progress compared with the previous dossiers produced by Andra in that, for the first time, it explicitly envisages the influence of climate changes on the hydrogeological model and on the biosphere. A finer appreciation of climate sequencing could result in greater detail being provided for these assessments. It must however be emphasised that any effort in this area must be set against the uncertainties weighing on the evolution of the surface environment, encouraging the adoption of very robust and partly stylised approaches.

Characterisation of the transport properties of the excavation damaged zone, immediately after sinking, then their evolution under effect of mechanical or even thermo-mechanical constraints in the concerned disposal cells, is an important subject for which the underground laboratory has already started and will continue to contribute important information. Today the EDZ assessment is conducted by modelling; the data obtained during experiments will enable specifying the mechanical behaviour of the rock with the aim of optimising the concepts.

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Modelling of transient phases also requires pursuing the works for representation of the coupled phenomena. The Dossier 2005 has already built on the transport-chemistry coupled calculations that allowed specifying the phenomena extension. Detailed understanding of the earliest phases of life takes place through the pursuit of modelling work on couplings, including those induced by heat (thermo-mechanical behaviour of EDZ, pursuit of studies on the heat-transport coupling). Representation of coupling due to hydraulic transients –particularly models in an unsaturated medium - will also enable refining the control and understanding of the initial centuries of the repository's evolution with particular attention paid to controlling the conditions in which the materials evolve over time in the repository.

The continuation of studies into the conditions under which corrosion develops within the repository should enable the conceivable speed ranges to be reduced by approaches which are both theoretical (for example, coupling with modelling in an unsaturated medium) and experimental (with possible experiments in situ on metallic materials). It is possible that we could therefore revise the corrosion gas pressure build-up assessments downwards and, through this, the influence of the gases on the hydraulic transient. Furthermore, by studying the various hydrogen migration pathways, it will be possible to provide further detail for the overall evolution diagram, based here too on modelling and a more experimental approach.

Finally, as a result of the qualitative safety analysis, it has been possible to draw up an initial list of processes, the implementation of which during the operating phase could restrict the duration of this phase from the point of view of long-term safety. Reversibility appears possible over a few centuries (typically two or three hundred years) or potentially longer periods. The design approach adopted by Andra, privileging joint, homogeneous treatment of the questions of safety and reversibility, leads to architectures in which these two notions do not appear to compete with each other. The same approach will be continued in the future.

12. *What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.*

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13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

14. Any other comments?

15. What are the key references that support your response?

INTESC I.4 Please provide a primary reference (e.g. a safety report, guidelines, regulations, standards…) and, if necessary, a small number of additional references that support your responses to this questionnaire.

INTERNATIONAL EXPERIENCE IN DEVELOPING SAFETY CASES- INTESC

Andra's answers to the questionnaire.

Primary references include the French Act and the series of reports submitted accordingly:

- The French Waste Act dated 30th December 1991 [1]
- The French Safety rules namely RFS.III.2.f, guidelines [4].
- Synthesis Report, Evaluation of the Feasibility of a Geological Repository, Meuse/Haute-Marne Site (in English and French) [5].
- Architecture and Management of a Geological Disposal System Report (TAG; C.RP.ADP.04.0001) (in English and French) [6].
- Phenomenological Evolution of the Geological Repository Report (TEP; C.RP.ADS.04.0025), (in English and French) [7].
- Assessment of Geological Repository Safety Report (TES; C.RP.ADSQ.04.0022) (in English and French) [8]

1) Loi n°91-1381 du 30 décembre 1991 relative aux recherches sur la gestion des déchets radioactifs, Journal official du 1er janvier 1992.

2) Loi n°91-1381 du 30 décembre 1991 relative aux recherches sur la gestion des déchets radioactifs, Journal official du 1er janvier 1992.

3) Andra (2005) Analyse qualitative de sûreté en phase post-fermeture d'un stockage : liste des évènements extérieurs – Site de Meuse / Haute-Marne. Rapport Andra n° C NT AMES 04-0039.

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4) Direction de la sûreté des installations nucléaires, Règle Fondamentale de Sûreté III.2.f, Définition des objectifs à retenir dans les phases d'études et de travaux pour le stockage définitif des déchets radioactifs en formation géologique profonde afin d'assurer la sûreté après la période d'exploitation du stockage - Juin 1991.

5) Andra 2005, Dossier argile 2005, synthèse (English version will be available soon).

6) Andra (2005) Architecture et gestion d'un stockage géologique réversible – Dossier argile 2005. Rapport Andra n° C RP ADP 04-0001 (English version will be available soon).

7) Andra (2005) Evolution phénoménologique du stockage géologique – Dossier argile 2005. Rapport Andra n° C RP ADS 04-0025 (English version will be available soon).

8) Andra (2005) Evaluation de sûreté du stockage géologique – Dossier argile 2005. Rapport Andra n° C RP ADSQ 04-0022. (English version will be available soon).

A7 France - IRSN

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	IRSN
Responsible Person(s):	Christophe serres
Date:	01/12/2007

1. *What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?*

See Andra contribution

2. *What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?*

Basic safety Rule III.2.f related to deep geological repository of LL-HLW.

3. *How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.*

4. *How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.*

See Andra contribution

Uncertainties may be encompassed through special design provisions or by adopting hypotheses increasing their effects and studying the consequences on global installation safety of a partial or total loss of function of the various repository components. IRSN considers that uncertainties over the evolution of containment performances of engineered repository components (packages, over-packs, seals) may be taken into account by postulating failures of these components with varying degrees of severity.

Complement from IRSN:

Use of modelling approaches aiming at testing the robustness of the repository for possible components failures or postulated states and environmental conditions.

Concerning the French case in Callovo-Oxfordian formation, IRSN considers that the possible effects of a hypothetical fracture crossing the geological barrier must be assessed. IRSN considers in fact that although the properties of the Callovo-Oxfordian formation seem overall favourable to containing radioactivity, the current state of knowledge is insufficient to conclude that the tectonic damage (fractures) of the clay formation is as slight as observed in the laboratory over all the zones in the

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sector likely to host a potential repository, or to disregard the possible effects of an earthquake on the host formation, right below the structures potentially detected under this formation. IRSN studies have nevertheless shown that the consequences of this type of short-circuiting are in principle minor as soon as sufficient clearance distance is maintained between the fracture and the engineered repository structures.

5. *How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.*

6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?*

IRSN intends to conduct a preliminary study aiming at identifying assets of the probabilistic calculation types for the long-term evolution of the total-repository-system assessment. The integrated analyses carried out so far by IRSN are exclusively of deterministic type. The international community has been using widely probabilistic calculations; ANDRA is developing such probabilistic computational capacity. Consequently, it is useful that IRSN acquires a capacity of analysis for this type of computational method.

Because of the large amount of memory and computer time required for running 3D radionuclide transport models, it is unrealistic to couple this model with probabilistic subroutines. It is the reason why IRSN prefer study a process of simplification of the model to allow a statistical treatment of uncertainties linked to variation of parameters as well as to the different conceptual assumption. Simplification process combined with probabilistic approach is judged by IRSN as complementary to the deterministic 3D one aiming at integrating as realistic as possible features and possible alteration and dysfunction of the system governing RN transport and radiological impact. This methodology for PA/SA is consistent with safety approach preferred by IRSN and Nuclear Safety Authority which is based on a stepwise collection of arguments conceived upon defence in depth principle but not risk-based principle.

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7. *How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.*

8. *What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.*

9. *What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.*

Design adaptation:

- limitation of high temperatures to preserve favourable and known physical and chemical environment (the envisaged repository concepts should prevent rises in temperature that could prejudice the containment capabilities of the repository components, adoption of an over-pack is relevant to prevent releases of activity in temperature conditions where transport phenomena are poorly controlled…)
- seals designed with narrow trenches to intercept EDZ
- dead end architecture of disposal tunnels
- location of shaft and repository areas with respect of mapped structures and underground flow patterns

Seeking for national/international consensus: for example, hypotheses describing biosphere can not be based on strict technical expertise but must rely as much as on possible consensus of various stakeholders concerned

10. *What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?*

Base data:

- wastes : inventory (amount and volume) of waste generated depend on operating hypotheses which may vary in time, degradation kinetic
- geological/hydrogeological data: presence and role of fractures in the clayey

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host rock formation and surrounding limestone layers

- response spectrum for earthquake and possible effect on host rock

Changes in repository components

- margins for thermal dimensioning
- characterisation of gas release (corrosion) and transfer in poorly desaturated media and complex components (seals or plugs)
- mechanical behaviour of rock and extension of EDZ around excavations
- transient state of cement, steel and clay components under repository conditions

Construction and Operational phase, Long term behaviour of repository and dosimetric impact (long term performances will depend on the initial and real state of the components during construction and operational phase

- How to practically measure the level of quality which will be actually reached in situ for the various components of the repository: methods, process, quality control to detect defects (e.g. of canisters…) and account for effects of natural heterogeneities and defects due to in situ manufacturing,
- How to derive from this measurement the in situ performance of component? what will be the criteria, function indicators upon which (below which) the long term performance of the component should lead to an altered evolution of the repository?
- influence of the repository chemical environment conditions occurring during transient phase on confinement properties of components and long term behaviour of repository
- extrapolation of canisters and seals performance over period of time not available to experiments and in situ monitoring (in connection notably with interactions during short or longer transient phase)
- derivation and classification of evolution scenarios according to the level of confidence in the specified characteristics of the components, the tolerance, deviations from specifications…
- biosphere and model transfer for radionuclides likely to cause the major dose (I129, Cl36…)

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Responsible Person(s):	Christophe serres
Date:	01/12/2007
11. How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.	
Needs for demonstration tests in situ.	
12. What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.	
13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.	
14. Any other comments?	
15. What are the key references that support your response?	

A8 Germany - BGR, DBE, GRS

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Organisation(s):	BGR, DBE, GRS
Responsible Person(s):	D.-A. Becker (GRS), N. Müller-Hoeppe (DBE TEC), J. R. Weber (BGR)
Date:	15. Jan. 2007

1. *What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?*

Radioactive waste with negligible heat generation: The Konrad repository is licensed, but a lawsuit pertaining the license has been filed and is pending

Low- and intermediate-level waste: The Morsleben repository ERAM was licensed in the former German Democratic Republic and was operated until 1998. The approval procedure for backfilling and sealing is in progress.

HAW: The Gorleben Salt Dome was investigated as a potential repository site for all types of radioactive waste. The detailed site characterisation was interrupted in 2000 for political reasons.

The performance of a new site selection procedure is presently discussed.

2. *What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?*

In 1983 the then responsible Federal Ministry of the Interior published safety criteria for the final disposal of radioactive waste. These criteria specify the maximum acceptable individual dose limit. The criteria do not include requirements pertaining to treatment of uncertainty. An amendment of the safety criteria is under way.

3. *How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.*

Uncertainties are classified in the following categories:

Scenario uncertainties: Means, that a scenario has a probability of occurrence, which is very uncertain and can only roughly be estimated.

Model uncertainties: In some situations, it is unclear, which model has to be applied for describing a specific effect or part of the repository. It may, e.g., be unknown whether the radionuclides take one or another way through the host rock, and these two possibilities may require different models.

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Responsible Person(s):	D.-A. Becker (GRS), N. Müller-Hoeppe (DBE TEC), J. R. Weber (BGR)
Date:	15. Jan. 2007

Parameter uncertainties: Nearly all parameters of an integrated PA study are more or less uncertain. This can be due to poor knowledge about the system or its future development, an insufficient experimental basis, or principal reasons. In the latter case, the parameter uncertainties have to be accepted as a physical fact, and are called aleatoric. Uncertainties, however, that can, in principle, be reduced by additional measurements or improved system investigation are called epistemic.

4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

Scenario uncertainties: If its probability of occurrence seems very low, a scenario is excluded from further investigation. Normally, an undisturbed evolution scenario is considered, and, additionally, a low number of disturbed evolution scenarios. Since the probabilities of occurrence are very uncertain, the scenarios are chosen such that they represent, as far as possible, the worst cases. The selected scenarios are considered independently.

Model uncertainties: In the case of a known model uncertainty, the probabilities of alternatives are estimated and a parameter is defined that switches between the respective models, depending on its value, in a probabilistic analysis. This technique was used, e.g., to consider different possible transport paths within the ERAM repository.

Parameter uncertainties: Uncertain parameters are analysed and an adequate distribution function is defined for each of them. If, e.g., only an interval of possible values is known, a uniform distribution is chosen, if a preferred value is known within the interval, a triangular or normal distribution is chosen. For deterministic calculations, parameters are preferably taken from the conservative end of their interval, but sometimes, this is not unique. Parameter uncertainties are best treated with a probabilistic approach. Aleatoric and epistemic uncertainties require, in principle, their own techniques of analysis, but in reality, most uncertainties can be considered to be epistemic.

A detailed probabilistic uncertainty analysis for a generic HLW repository was done in the SAM study [1].

The methodology was also applied for the long term safety assessments of the ERAM LAW repository and the ASSE mine.

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Organisation(s):	BGR, DBE, GRS
Responsible Person(s):	D.-A. Becker (GRS), N. Müller-Hoeppe (DBE TEC), J. R. Weber (BGR)
Date:	15. Jan. 2007

5. *How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.*

Presently, an important uncertainty is the behavior of the EDZ during saturation. As the EDZ is coupled to the access shafts and drifts it must be regarded as a potential pathway. In PA the flow resistance of the EDZ is included into the flow resistance of a geotechnical barrier. Practical experience shows that the hydraulic behavior of the EDZ depends significantly on mechanical stress state during saturation. This aspect is not always included in PA.

Another important issue is the compaction of crushed salt. Uncertainties exist about the development of the compaction process at very low porosities and require conservative assumptions.

6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?*

Integrated PA is done with essentially simplified 1-D models in order to allow for computing long time frames within a reasonable real time. If a lot of uncertainties exist, a simplified approach seems acceptable. The results, however, must not be misinterpreted as an exact prognosis of future effects but as a safety indicator. Deterministic reference case calculations and local parameter variations are performed to increase the general understanding of the system. As far as possible, parameters are chosen conservatively, but in many cases conservativity can not be proven. Therefore, it is always necessary to complement the deterministic calculations by a probabilistic uncertainty and sensitivity analysis.

7. *How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.*

A statement about the safety of a repository is only possible if the level of confidence in the calculated results is known. Therefore, uncertainty analysis is a necessary part of all comprehensive safety assessment studies. The uncertainty is analysed probabilistically by performing a number of runs with randomly chosen parameters. There are different requirements to the uncertainty analysis. Proposed regulations require that, with a confidence level of 90 %, the 90%-quantile of the calculated results be below the limit, which is a rather weak criterion and can be proven with a low number of runs. A more detailed uncertainty analysis, yielding information about the distribution of results, requires several hundreds of runs.

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The sensitivity analysis is first performed as a local sensitivity analysis with deterministic parameter variations, and then as a probabilistic global sensitivity analysis, ranking the parameters after their global influence on the result. Generally, it requires a larger number of runs than the uncertainty analysis. Different linear and non-linear methods for sensitivity analysis are known. The task is independent of the uncertainty analysis, but often done within one step and using the same set of calculations.

8. What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.

A proper uncertainty analysis can yield information about the existing uncertainties, but not reduce them. To prove the safety of a repository, it is sensible not only to rely on one line of argument. Additional safety indicators, such as radionuclide flows and concentrations, can improve the safety statement by excluding a complete field of uncertainty, e.g. all uncertainties relating to the biosphere, and using completely different safety measures. This has been tested in the SPIN project [2].

The uncertainty of the safety statement can also be reduced by means of additional, over-conservative investigations that only use data of low uncertainty. For example, the radiotoxic inventory of the repository can be compared with the natural radiotoxicity of the surrounding rock, and by showing that it falls under this reference after some time by decay, one can establish a limited timeframe, during which a proper functioning of isolation measures is necessary. Such an investigation has been done for the ERAM repository.

9. What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.

Classical engineering methods, e.g. a safety oriented repository design (safety design), improvement of the natural system, proof of structural reliability of important design elements to reduce variation ranges of their safety related characteristics, and QA.

10. What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?

The HM coupling of the EDZ acting in parallel to geotechnical barriers and the long-term evolution of the geotechnical barriers. In case of salt rock the behavoir of the EDZ and the geotechnical barriers of a well designed repository are decisive for the classification of brine intusion scenarios (undisturbed or disturbed).

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Date:	15. Jan. 2007

From the scientific point of view the likelihood is small, in public communication, however, this uncertainty can not be neglected.

11. How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.

If uncertainties affect safety, engineering measures are used to reduce uncertainty, e.g. by an optimized design.

12. What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.

German RTDC1 participants have no experience in communicating uncertainty in different ways.

13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

There are no unique rules for establishing the distributions of uncertain parameters. Distributions and intervals are often chosen more or less arbitrarily, which leads to results of the uncertainty analysis that themselves are uncertain. A similar problem exists with parameter correlations; sometimes there is a vague feeling that two parameters are statistically correlated, but there is no unique rule to quantify the degree of correlation. Internationally accepted rules for analysing the knowledge about uncertain parameters and their correlations should be established.

Moreover, there are no unique rules for performing a probabilistic uncertainty analysis and assessing its results. It is unclear, how many runs should be made, which criteria should be fulfilled, and how the results should be communicated to the public. In Germany, there are no regulatory rules so far. An international consensus would be desirable.

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Organisation(s):	BGR, DBE, GRS
Responsible Person(s):	D.-A. Becker (GRS), N. Müller-Hoeppe (DBE TEC), J. R. Weber (BGR)
Date:	15. Jan. 2007
14. Any other comments?	
15. What are the key references that support your response?	
[1] D. Buhmann, A. Nies, R. Storck: Analyse der Langzeitsicherheit von Endlagerkonzepten für wärmeerzeugende radioaktive Abfälle. GSF Bericht 27/91 [2] D.-A. Becker et al.: Testing of safety and performance indicators (SPIN), EUR 19965EN, Brussels 2003.	

A9 Japan - NUMO

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	Nuclear Waste Management Organization of Japan (NUMO)
Responsible Person(s):	K. Ishiguro, K. Wakasugi
Date:	07/02/19

1. What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?

Taking into account the technical achievement of generic feasibility study over last twenty years, which was integrated in JNC's H12 [1], the Japanese programme for geological disposal of HLW stepped into an implementing phase with the promulgation of the "Specified Radioactive Waste Final Disposal Act" (hereinafter referred to as "the Act") in June 2000. Following the Act, NUMO was established in October 2000.

The Act specifies that the siting process shall consist of three steps. Firstly, Preliminary Investigation Areas (PIAs) for potential candidate sites are nominated based on site-specific literature surveys (LS) focusing on long-term stability of the geological environment. Secondly, Detailed Investigation Areas (DIAs) for candidate sites are then selected from PIAs following surface-based investigations, including boreholes, carried out to evaluate the characteristics of the geological environment. Thirdly, detailed site characterisation, including investigations using underground research facilities, leads to selection of the site for repository construction. According to the present schedule, repository operation may start as early as the mid-2030s.

NUMO announced the start of open solicitation of volunteer municipalities for PIAs with publication of an information package on December 19, 2002 and has been at the first stage of the siting process. NUMO just received an application from Toyo town in Kochi prefecture, effective as of January 25, 2007. NUMO initiated an internal procedure that includes confirming the geological conditions in Toyo town. The LS will be started off in the near future. NUMO is continuing to call for other municipalities to apply as volunteer areas for exploration.

In accordance with the new framework specified by the Atomic Energy Commission of Japan, JAEA (successor of JNC) continues to be responsible for R&D activities aimed at enhancing the reliability of disposal technologies and establishing safety assessment methodologies and associated databases. JAEA has thus been actively promoting R&D aimed at contributing to the implementation of disposal by NUMO and to the safety regulations to be formulated by the Nuclear Safety Commission of Japan (NSC) and the Nuclear and Industrial Safety Agency (NISA).

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Responsible Person(s):	K. Ishiguro, K. Wakasugi
Date:	07/02/19

2. What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?

Although regulatory compliance requirements have not been defined yet, NSC[2] and NISA[3] have been discussing the framework of the regulation of HLW repository. More recent NSC report on common key issues for radioactive waste disposal suggests the need to consider scenario-based criteria by classification of assessment scenarios based on the possibility of occurrence, with specifying corresponding dose constraints.

3. How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.

The long-term safety of a given geological disposal system cannot be assessed conclusively due to the incompleteness of our knowledge about the system and its future behaviour. These uncertainties can be classified into the following types in the H12 report [1]:

- Scenario uncertainty: Scenario uncertainty arises from limited knowledge of the evolution of processes such as chemical interactions, the timing and frequency of events on geological environment and future human activities.

- Model uncertainty: In some cases, two or more alternative conceptual models are able to explain the observed behaviour of phenomena equally well, but lead to significantly different predictions when they are used to extrapolate the observations over time and/or space. This is one source of model uncertainty. Model uncertainty can also arise from possible errors in formulating and simplifying mathematical equations and in programming software.

- Data uncertainty: Data uncertainty arises from measurement errors, interpolation of spatially heterogeneous geological properties and extrapolation of results of experiments and natural analogue studies over times and conditions relevant to the assessment.

It's noted that there is another types of uncertainties, stochastic variability and lack of knowledge, referred to as Type A and Type B, respectively. It can be thought they express the difference of sources about uncertainties. On the other hand, the former classification expresses the treatment of uncertainties in the PA.

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4. *How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.*

The treatment of the uncertainties has not been determined yet in NUMO. But the same manner as that dealt with in the H12 report [1] will be used at the early stage of site investigation. The general treatments of the deferent uncertainties are as follows. See also Table 1 for another categorization and its treatment in the H12.

- Scenario uncertainty: The scenarios are classified into base case scenario, altered scenario and destructive event scenario. The altered scenario and the destructive event scenario are evaluated as a what-if like scenario.
- Model uncertainty: A deterministic analyse are performed using an altered model from the model which is used at the reference case. (e.g. colloid transport model)
- Data uncertainty: A deterministic analyses are conducted using varied parameters from those used at the reference case analysis.

The treatment of uncertainty will be affected by the requirements of the regulatory body.

5. *How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.*

Major uncertainties have not been identified because site characterization has not been commenced yet. General perspective is described as follows [4].

Generally, available literature and site-specific database could be quite limited at the early stage of site investigation, in particular, the LS stage and the largest uncertainties may be associated with the geological environment. Little weight should then be placed on barrier performance of the geosphere at this stage, but EBS or near-field processes may be able to provide a robust safety case with minimal performance from the geosphere (predominantly isolation and protection of the EBS). Qualitative arguments in the safety case may be more meaningful than quantitative PA calculations at this stage, to scope uncertainties and identify data requirements for the preliminary investigation (PI) programme and to provide strategy and guidance for the development of the repository concept and safety case at later stages.

At the PI stage, in which field investigations are initiated, more detailed technical evaluation is required within the safety case in order to justify the important (and politically sensitive) selection of DIAs. At this stage, the safety case will include

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more quantitative evaluations based on surface geological investigations and modelling, although availability of geological information will still be limited and significant uncertainties may remain. Site-specific data, based on several boreholes and geophysical investigations, will be available for the repository concept and safety case development, although again the importance of remaining uncertainties needs to be borne in mind. An emphasis may still be placed on EBS performance in cases with limited geological information or complex and heterogeneous geology [5]. The safety case at this stage also provides guidance for subsequent, more detailed investigations (including that in underground characterization facilities at the DIAs) to reduce any identified uncertainties in the geological database.

6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?*

Since there are many approaches for PA, they should be used appropriately depending on the purpose of PA. The fig.1 shows modelling strategy in NUMO [5]. Process models express the behaviour of sub-system or system components in detail. System models integrate all process models conservatively and describe the behaviour of total system and safety relevant view.

At the LS stage, the available literature and site-specific database may be quite limited, so PA will be conducted by using a simple system model and generic data set. Since the largest uncertainties at this stage will be associated with the geological environment, uncertainty analysis is mainly focused on the site descriptive model for the geological environment such as groundwater flow (note qualitative arguments about uncertainties may be more meaningful than quantitative PA calculations at this stage). The deterministic approach may be used in order to provide a transparent assessment of sensitivity of the system to variations in the geological condition. The results will be reflected the selection of the PIAs.

At the PI stages, the surface-based investigations, including borehole survey and geophysical prospecting will be conducted. The uncertainty analysis based on the site-specific data will be performed to select the DIAs. Since available geological information will still be limited and significant uncertainties may remain, probabilistic approach, stochastic approach or use of fuzzy mathematics using the system model may be appropriate to give feedback information to site characterization works and R&D (e.g. priorities of the further investigation and key issues). ((i), (ii) in the fig.1)

At the DI stage, NUMO will be required to provide all safety relevant evidence including information to be associated with uncertainties to make a decision by stakeholders whether NUMO can go into the construction phase or not. In this

(v) License Application

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situation, it is important that NUMO understands the system behaviour by using process model (often complex models) as realistic as possible and quantifies the safety margin by comparing the results from system model ((iii), (iv) in the fig.1). The system model at this stage should be simple and easy to understand to promote an understanding of stakeholders, while considering the results of process models ((v) in the fig.1). In any case, what types of approach and model (deterministic or probabilistic, realistic or conservative, etc.) we use is strongly dependent on requirement from the regulator.

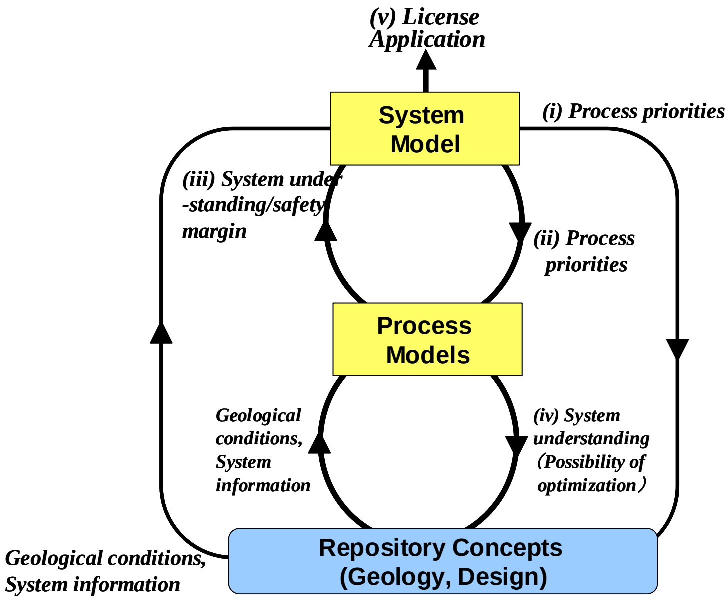

Fig.1 Modelling strategy of NUMO

7. How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.

NUMO hasn't decided detail methodology for PA yet, since the site characterization has not been commenced. But the same manner as that dealt with in the H12 report [1] will be used as a fundamental PA methodology. In the H12 report the assessment consists of the following steps (see the fig.2);

- Reference Case based on the reference system and reference design is defined in order to provide a central case for comparison of numerous calculation cases.
- Sensitivity analyses are performed to understand the response of system performance to uncertainties in scenario, model and data, and alternative geological environment cases and alternative design cases to address various geological disposal systems.

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- The key phenomena and uncertainties are identified based on the results of sensitivity analyses.
- To evaluate the system safety, the combinations of uncertainties and variations are considered in the total system performance analysis. The rational combinations are considered to reduce to a number that is manageable using a deterministic approach.
- The results are compared with some safety standards.

Sensitivity analyses provide that which deviations from the likely characteristics and evolution the system affect overall performance and the performance of individual system components. These analyses should be performed prior to the total system performance analysis to make a number of analysis cases more reasonable and manageable. Uncertainty analysis wasn't defined explicitly in the H12 report.

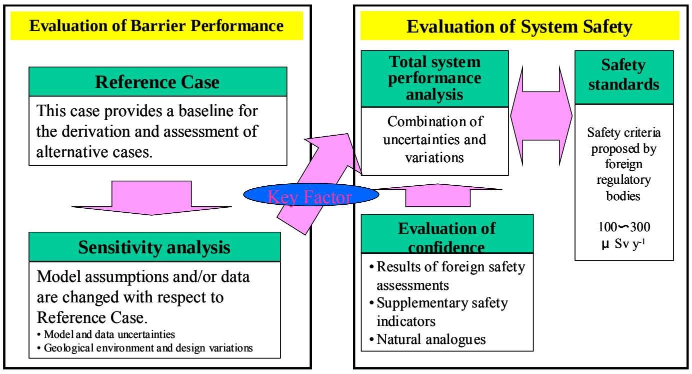

Fig.2 Procedure for PA in the H12 report

8. *What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.*

- JNC (2000): H12 Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, Project Overview Report, 2nd Progress Report on Research and Development for the Geological Disposal of HLW in Japan, JNC Technical Report TN1410 2000-001, Japan Nuclear Cycle Development Institute, Tokai-mura Japan.

- NUMO (2004a): Evaluating site suitability for a HLW repository – Scientific background and practical application of NUMO's siting factors, Nuclear Waste Management Organization of Japan, NUMO-TR-04-04.

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Responsible Person(s):	K. Ishiguro, K. Wakasugi
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9. *What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.*

- Peer review by independent experts
- Appropriate management methodology or tools (e.g. QMS, NSA, RMS)

In order to maintain flexibility without losing focus and make the work more systematic, NUMO has developed a formalised tailoring procedure, termed the NUMO Structured Approach (NSA)[4]. The NSA provides a methodology for developing repository concepts in an iterative manner, which couples management of immediate issues with consideration of longer-term developments. The NSA also guides the interaction of the key site characterisation, repository design and PA groups and is facilitated by tools to help the decision-making associated with the tailoring process (e.g. a requirement management system, RMS) and with comparison of siting and design options (e.g. multi-attribute analysis). The RMS is being developed to help implement the NSA . This RMS will allow the justifications, supporting arguments and knowledge base used for every decision to be clearly recorded and will highlight when such decisions may need to be revisited, for example due to changing boundary conditions or technical advances. It thus serves as a valuable tool to keep track of the wide range of constraints on designs, while the entire process runs within an overarching Quality Management System (QMS). NUMO has developed its own QMS to ensure high quality of all its technical activities, documents and databases. The QMS will be integrated within the RMS, to ensure the total quality of the repository project, including the safety case development [4].

10. *What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?*

The main uncertainties at the generic PA are listed in Table 1 based on the H12 analysis [1]. However the largest uncertainties may be associated with the geological environment as available literatures and site-specific database could be quite limited at the early stage of site investigation. See also the answer for the question 5.

11. *How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.*

Since NUMO's strategy for safety case development is constrained by a staged siting approach, uncertainty analysis will be used depending on the objectives of PA in the each stage.

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Responsible Person(s):	K. Ishiguro, K. Wakasugi
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The aim of PA at the LS stage is to illustrate fundamental safety of the repository concept at the volunteer site, utilising evidence from the literature information for the site, complemented by generic and international experiences. Generally, available literature and site-specific database may be quite limited. At this stage the uncertainty analysis will be used to identify key uncertainties that will be associated with geological environment. Another objective of uncertainty analysis at this stage is to provide information to the selection of PIAs, and the strategy and guidance for the site investigation in the PI stage.

At the PI stage more detailed technical evaluation is required in order to justify the selection of DIAs. At this stage, site-specific data, based on several boreholes and geophysical investigations, will be available for the repository concept (RC). So the uncertainty analysis in this stage will be used to compare between the potential areas for DIA and their system design options.

The PA at the DI stage will be required to be more convincing and complete to justify the construction of a repository at a selected DIA and to demonstrate compliance with regulations. Site-specific data from the underground experimental facility will be a significant input for the development of the RC. The uncertainty analysis using process model which can deal with detail process/barrier geometry may be useful to understand system behaviour and optimize the repository design. The uncertainty analysis using system model may be useful to identify key issues (see fig.1). In the safety case, NUMO will submit all safety relevant evidence including results of uncertainty analysis to make a decision by stakeholders as the licence application. The uncertainty analysis in the safety case may complement the robustness with respect to satisfying the safety criteria.

12. What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.

13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

14. Any other comments?

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	Nuclear Waste Management Organization of Japan (NUMO)
Responsible Person(s):	K. Ishiguro, K. Wakasugi
Date:	07/02/19

15. What are the key references that support your response?

[1] JNC (2000): H12 Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, Project Overview Report, 2nd Progress Report on Research and Development for the Geological Disposal of HLW in Japan, JNC Technical Report TN1410 2000-001, Japan Nuclear Cycle Development Institute, Tokai-mura Japan.

[2] NSC (2004): Common key issues for developing safety regulations for radioactive waste disposal (in Japanese).

[3] NISA (2003): Discussion to establish the basis for the safety regulations for HLW disposal (in Japanese).

[4] K. Kitayama et al.: Strategy for safety case development: Impact of a volunteer approach to siting a Japanese HLW repository, presented at OECD/NEA international symposium on Safety Case for deep geological disposal of radioactive waste: Where do we stand?, Jan. 23-25, 2007, Paris.

[5] K. Ishiguro et al.: EBS Modelling for the Development of Repository ConceptsTailored to Siting Environments, OECD/NEA, Engineered Barrier Systems (EBS) in the Context of the Entire safety Case, Workshop Proceedings, La Coruna, Spain 24-26 August, 2005.

Table 1

System component	Uncertainty	Treatment
NEAR-FIELD		
Glass	• long-term dissolution rate / glass surface area • radionuclide solubility	• conservative constant dissolution rate / glass surface area • conservative and constant solubility based on the internationally recommended / in-house developed TDB • sensitivity analysis for dissolution rate
Overpack	• long-term corrosion rate • gas generation	• conservative constant corrosion rate • sensitivity analysis for overpack life time • neglected based on realistic corrosion rate
Buffer	• alteration (functional losses of colloid filtration and diffusion barrier) • radionuclide sorption • gas migration	• negligibly low possibility in the reference design (More recently, it is expected the research progress on buffer alteration such as Fe/bentonite interaction, cement/bentonite interaction and thermal effect etc.) • constant, conservative Kds • neglected based on experimental support of buffer self-sealing effect
Tunnel support (for soft rock)	• effects of cementitious material on groundwater chemistry	• use of low alkaline cement neglected in the case of low alkaline cement
Plug/grout	• long-term sealing effect	• analysis for seal failure scenario
EDZ	• groundwater flow • sorption	• conservative constant flow rate • sensitivity analysis for flow rate • neglected conservatively

System component	**Uncertainty**	**Treatment**
GEOSPHERE		
Host rock	• spatial variability in hydraulic gradient and transmissivity • geometry of flow porosity / channeling • spatial variability in Kds • colloid-facilitated transport	• probabilistic distribution of transmissivity / conservative hydraulic gradient • conservative geometry and flow-wetted surface • conservative constant Kds • analysis of colloid-facilitated transport
Major Water Conducting Faults	• transmissivity • location	• conservative constant transmissivity • conservative migration distance in geosphere (fault is assumed to be located at 100 m away from repository)
Geosphere/Biosphere interface	• location • Boundary conditions (e.g. dilution volume)	• consider possible alternative location • constant value depending on the GBI
BIOSPHERE		
	• lifestyle • surface environment	• stylised approach • possible alternatives in climate change
TOTAL SYSTEM (for all components)		
	• natural phenomena • initial defects	• what-if or stylised approach (probability may increase after 10^5 years depending on the geological stability) • what-if approach
	• future human intrusion (e.g. probability drilling at the site, drilling a well, etc)	• stylised approach using probabilistic manner

A10 Netherlands - NRG

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	NRG
Responsible Person(s):	J. Grupa, J. Hart
Date:	13-12-2006

1. What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?

Concept assessment.

2. What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?

The Dutch legislative and regulatory framework governing the safety of spent fuel and radioactive waste management is contained in:

- the Nuclear Energy Act (1963, as amended 2004);
- the Environmental Protection Act (1979, as amended 2002);
- General Administrative Law Act (1992, as amended 2003);

In The Netherlands there are presently no specific requirements for the long term safety of a radioactive waste disposal system, since there is no intention to dispose radioactive waste in a geological disposal system in the near future.

Still, the general radiation protection requirements apply (very similar to the ICRP radiation protection principles), and also prescriptions following from the standard format of the Environmental Impact Statement apply.

Moreover, based on the existing safety studies for the generic disposal concept, specific requirements are expected to address the following issues:

1. Probabilistic analyses to obtain estimates of uncertainty bandwidths.
2. Monitoring of the system to detect unexpected behaviour, i.e. behaviour ‘outside’ the uncertainty bandwidth.
3. If the system develops to a situation outside the foreseen uncertainty bandwidth, if necessary mitigative actions can be undertaken up to the extent of retrieval of the waste.

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Organisation(s):	NRG
Responsible Person(s):	J. Grupa, J. Hart
Date:	13-12-2006

3. How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.

A generic probabilistic safety analysis (PROSA, [1]) 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.

Within each scenario, uncertainties are treated by determining suitable probability density functions for the values of the model parameters (or probabilities of specific values if the parameter is discrete), followed by a large computational effort including statistical pre- and postprocessing to determine probability density functions for the individual effective dose.

This approach implies two main types of uncertainty:

a. It is uncertain which of the selected scenarios will cover the actual future development of the disposal system.

b. It is uncertain what the precise model representations are of the actual development even if it would be known which scenario is applicable. This type of uncertainty includes conceptual model uncertainty (i.e. how a system is subdivided into "nodes"), modelling uncertainty (how accurate are descriptions of the various phenomena), and uncertainty in the mode data.

In PROSA, the second type of uncertainty is simulated by applying suitable bandwidth in the model parameter values ('parameter uncertainty'). This also covers model uncertainty: if a mathematical model has only limited applicability, this is 'stretched' to the applicability needed by increasing the bandwidth of the values of the model parameters.

Parameter uncertainty is covered by determination of an adequate probability density function for the value of the model parameter. In practise, however, for most of the more complex processes, the bandwidth of the value of a model parameter is dominated by model uncertainty.

Example: the probability density function of the subrosion rate of a salt dome is based on measurements of many similar salt domes, and determination of the long term history of the subrosion rate. This has to be regarded as a simplification of more complex geophysical models that describe the spatial development of a salt dome.

In some cases model uncertainty is linked to scenario uncertainty, since the selection of a specific scenario implies the application of dedicated models to address the role

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of given 'features, events and process' in the selected scenario.

Example: the biosphere model needed to calculate exposure of humans to radioactive material in groundwater is modelled as a present day small scale agricultural community. The use of this model is prescribed by the selected scenario.

A special 'Reliability Assessment' was included in PROSA which implies motivated and explicit decisions on how to deal with model uncertainties (e.g. treatment by scenario definition or by additional parameter-uncertainty).

The so-called 'conceptual model uncertainty' has not been dealt with explicitly in PROSA. Conceptual models are built on the basis of features like legal requirements, availability of and experience with computer codes, and availability of time/recources. In addition, knowledge, experience and expert judgement are important prerequisites for building a conceptual model. As such, the influence of the modeller on the final results might be significant. This might imply that conceptual model uncertainty can be a dominant type of uncertainty.

'Conceptual model uncertainty' can be addressed by external reviews and comparisons with other studies (benchmarking).

4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

Scenario uncertainty:

In PROSA very unlikely scenarios have been screened out and were not analysed. Unlikely scenarios and probable scenarios were treated on an equal basis. i.e. in the overall assessment it was assumed that the probability of each selected scenarios is almost 1. This assumption is equivalent to use a deterministic 'worst case' analysis for a safety assessment rather then a probabilistic analysis.

Example: the calculated doses in the PROSA study [1] from the brine intrusion scenario are presented and evaluated as if the scenario would occur, although the scenario is actually unlikely. The reason is that the calculated maximum doses are almost six orders of magnitude below the natural background, so for the purpose of that study there is no further benefit in considering the probability of this scenario.

Model- and parameter uncertainty:

For each selected scenario a separate probabilistic analysis has been performed, where model uncertainty and parameter uncertainty are all translated into parameter uncertainty.

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Example: the plastic behaviour of rock salt was modelled by an analytical model that was tuned by measurements and detailed FE calculations. This was necessary because measurements are only limited available and FE calculations are only possible idealised geometries. However, it was possible to cover the model uncertainty by using suitable bandwidths for the model parameters (EVEREST [2]).

A safety case (that is wider than the probabilistic safety analysis in PROSA and EVEREST) has not been prepared. Conceptual model uncertainty is not addressed explicitly, but a safety case could provide a useful framework for this issue.

5. How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.

There are a thousand or more model parameters that have to be addresses in a full Performance Analysis. In a full probabilistic analysis for each of these parameters probability density functions have to be determined, and also cross-correlation functions. Without an initial screening procedure, the total number of probability density functions and cross-correlations is unmanageable.

In practise, the uncertainty in most of the model parameters does not contribute significantly to the uncertainty in the endpoints of the calculations, and does not correlate with the uncertainty in most other model parameters. This allows a screening procedure that reduces the number of parameters to be addressed in a probabilistic analysis to manageable proportion.

The initial screening is essentially an expert judgement activity. Since the model parameters are inseparable from the associated model, and the model is connected to a process, (feature or event), in PROSA [1] the initial screening can be combined with the scenario identification procedure. This allows a systematic documentation of the expert judgement rationales for all models and associated model parameters.

Example: In PROSA, radiolysis (FEP 3.4.5) is judged to be of minor importance. This implies that also the model parameters related to radiolysis do not have to be addressed in the probabilistic analysis.

The determination of the probability density functions and correlations for the selected model parameters is often difficult and often also based on expert judgement.

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6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?*

A system PA consists of deterministic as well as probabilistic analysis. Deterministic analysis are used to get a good understanding of the performance of the system in various conditions.

In deterministic analyses the best available values of parameters have to be used. In addition, for parameters that are less well characterized conservative assumptions are implemented. Undue conservatism must however be avoided. To remove undue conservatism complex modelling is often required. For those parameters that will be addressed in probabilistic assessments realistic assumptions can be made, since the conservative assumptions will be part of the probabilistic assessment. In a broad sense, undue conservatism can be avoided amongst others by probabilistic analyses.

Probabilistic analyses usually require simplified models due to practical limitations to computational resources. Deterministic results with obtained with complexer models are used as 'benchmarks' for the probabilistic results.

Statistical tools for the probabilistic analyses can be complex, but are well defined in mathematics. until now the standard approaches (where we regard 'fuzzy mathematics' as non-standard) have been adequate.

7. *How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.*

There is a mathematically well defined difference between sensitivity and uncertainty.

If the endpoints of the calculation consists of n values (e.g. doses at various times, nuclide concentrations in given locations, etc.) these can be mathematically represented in a n-dimensional vector $\underline{r}$. The input parametervalues can be represented in an m-dimensional vector $\underline{s}$.

The sensitivity for a single input parameter s_i is defined as: $[d\underline{r}/ds_i]_{\underline{s}}$ (this includes correlations in $\underline{s}$).

To obtain sensitivities, a deterministic case has to be selected (represented by a specific $\underline{s}$), and no probability density functions for s_i are required. But sensitivity already includes cross correlations.

Commonly the mathematical sensitivity is normalised with respect to the bandwidth in s_i. This gives the opportunity to rank the various model parameters with respect to

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their sensitivity-impact on the endpoints of the calculations.

Alternatively, a number of deterministic calculations where one parameter (say s_p) is varied gives information about the behaviour of $[d\underline{r}/ds_p]_{\underline{s}}$ and can therefore be called a sensitivity analysis.

Example: in PROSA calculations have been performed for disposal facilities at various depth (from 200 to 500 m depths). The results showed that the maximum dose is relatively insensitive for the depth of the facility.

To obtain uncertainty bandwidths of the endpoints of the calculations, usually a probabilistic analysis is performed. The statistical techniques needed are more complex than in the above described sensitivity analyses. There are various techniques to rank the model parameters with respect to their impact on uncertainty in the endpoints.

Example: For the subrosion scenario the following statement is found in PROSA: "In case of the deep diapir (being the host rock)*, the probability for the dose rate to be greater or equal to 53 μSv/year is 1%."*

8. What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.

Uncertainty analysis is a sound scientific ingredient of a safety assessment. A probabilistic analysis gives additional endpoints such as total risk (rather than dose).

Confidence, or trust, or acceptance, are primarily not provided by uncertainty analyses.

Example taken from on a special issue of 'radiation protection dosimetry' on 'Expert Judgement And Accident Consequence Uncertainty Analysis' Special Issue, Vol. 90 No.3 2000}:

"The approach typically applied consisted of a scenario analysis comprising a great variety of exposure situations at the different stages of scrap processing, steel production and product use. It turned out that it was difficult to define the right degree of conservatism in defining the scenarios. (...) It was therefore decided to develop a stochastic simulation model to assess the distribution of individual doses to the general public committed by recycling of contaminated scrap. (...) This marked a breakthrough and paved the way for an overall concept of clearance which has been supported by probabilistic considerations in different areas. In the justification, however, a higher profile is given to a properly selected set of deterministic exposure scenarios."

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9. *What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.*

Uncertainties as dealt with within PA may cause logistic problems because of the large amounts of expert judgement decisions to be taken. This can be dealt with by coupling the issue to a systematic approach of scenario identification.

See also Question 5.

A clear distinction must be made between uncertainties that are dealt with in the PA, and uncertainties that are out of scope.

Example: in most studies operational issues of the disposal facility were seen as out of scope of the generic safety study. However, the issue of retrievability opened up scenarios like the pre-closure abandonment scenario 3]), which was originally out-of-scope. However, the treatment of this type of scenarios is actually independent of the issue of retrievability, i.e. the uncertainty with regards to the proper decommissioning of a facilty must be addressed in a safety case, irrespective of the retrievability issue.

This stresses the importance of a safety case, as this will put the embedded PA in perspective.

10. *What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?*

The PROSA probabilistic study has shown that large uncertainties arise from the hydrology in the overburden and in the amount of dilution in the exposure pathways in the biosphere. It is inherent in the disposal concept that engineered barriers and the near host rock must behave very reliable, which explains why these important parts of the disposal system do not dominate the uncertainty.

Example: The hydrology in the overburden, as well as the dilution in the biosphere are depending on far future climatic conditions. Within the next 100 000 years one or more ice ages are likely to occur. However, climatic models are unable to predict when. This causes a very broad bandwidth in possible local climatic and hydrological conditions.

It should be noted that the strength of the disposal concept is found in the reliable behaviour of the engineered barriers and the near host rock, as these systems are not affected by e.g. an ice age.

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11. How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.

Results of uncertainty analysis are reported, in general with the purpose to substantiate conclusions that were already drawn from deterministic analyses.

See Question 8.

More and more the dose limits used for license submissions are expanded to cover also probabilistic results.

Example: a limit like 'the dose should not exceed xx mSv' is adapted to probabilistic results as 'the probability to exceed a dose of xx mSv should be less then yy%".

Work programmes and priorities have to take into account that uncertainty analysis require a lot of effort.

12. What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.

A performance analysis is complex. The contribution of the uncertainty analysis to this complexicity is relatively small. The information should be presented in a wording that fits the audience. The complexicity therefore requires that much effort is given to the presentation. In practice, uncertainty can be communicated by using products as maps, graphs, tables, charts, flip books, images, and written or oral presentations. Selecting an appropriate product type and carefully crafting the contents can substantially reduce the likelihood of misunderstandings.

13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

There is a link between uncertainty analysis and scenario identification methodology that can be useful. The way this link can be utilised is however specific to the various analysis strategies.

A demonstration of this link is planned in RTDC 2 in the form of a formal scenario definition exercise and a combined uncertainty analysis of this scenario. The demonstration is focussed on the abandonment scenario that has deterministically

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addressed in the Dutch CORA [3] study. The two related activities are:

1. scenario definition by applying a formal expert elicitation procedure

2. an uncertainty screening followed by a probabilistic analysis of this scenario.

14. Any other comments?

-

15. What are the key references that support your response?

[1] *PROSA Study* Prij, J.,B.M. Blok, G.M.H. Laheij, W. van Rheenen, W. Slagter, G.J.M. Uffink, P. Uijt de Haag, A.F. B. Wildenborg and D.A. Zanstra, PRObabilistic Safety Assessment, Final report, of ECN, RIVM and RGD in Phase 1A of the OPLA Programme, 1993.

[2] *EVEREST Project* European Commission, EVEREST Project: Evaluation of Elements Responsible for the Effective Engaged Dose Rates Associated with Final Storage of Radioactive Waste: Summary Report, Rep. EUR 17122 EN, EC, Brussels (1996).

[3] *Expert Judgement And Accident Consequence Uncertainty Analysis* Radiation Protection Dosimetry , Special Issue, Vol. 90 No.3 2000.

CORA Study:

[4] B.P. Hageman (Chairman), *Terugneembare berging, een begaanbaar pad? Onderzoek naar de mogelijkheden van terugneembare berging van radioactief afval in Nederland*, Commissie Opberging Radioactief Afval, Ministry of Economic Affairs, The Hague, February 2001.

A11 Spain - ENRESA

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Organisation(s):	Enresa
Responsible Person(s):	Jesús Alonso Díaz-Terán
Date:	January 9th 2007

1. *What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?*

The Spanish programme for High Level waste disposal is at the stage of general feasibility studies. There are no definite plans at present to move into a new development stage.

The aim of on going activities in this field is the consolidation and update of the knowledge already acquired, taking advance of the new international developments.

2. *What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?*

The only acceptance criteria established by the Spanish Regulatory Body up to now is either that the individual equivalent effective dose does not exceed 10^{-4} $Sv.y^{-1}$, or that the individual annual risk does not exceed 10^{-6}.

There are no specific requirements on the treatment of uncertainty.

3. *How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.*

Three different types of uncertainties are considered:

- **System evolution uncertainty**, related to the prediction of the future evolution of the barriers of the system and the Biosphere.
- **Conceptual uncertainty**, related to the incomplete understanding of the nature of the processes involved in repository evolution.
- **Data uncertainty,** due to the limited amount of data available and the variability of the different input parameters to the models.

The previous classification already constitutes an example.

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4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

Each one of the three previous types of uncertainties has been dealt following different approaches:

- **System evolution uncertainty.** In addition to the Reference Scenario, other scenarios are defined and evaluated to study the sensitivity of the system performance to alternative assumptions on future system evolution.

- **Conceptual uncertainty.** Calculations are performed for different conceptual models and variants derived from the Reference Scenario.

- **Data uncertainty.** This uncertainty is considered through the use of probability distributions in the probabilistic calculations. The acceptability of results is assessed by comparing the average dose to the dose acceptance criterion (see question above)

For the two first types of uncertainty, the doses calculated are compared for each scenario, or in general, for each calculation case, to the dose criterion (there is not consideration for the probabilities of the scenarios). In all scenarios considered (with the exception of some intrusion scenarios) the calculated dose complies with the acceptance criterion.

In the Safety Assessment of a repository in clay (ENRESA 2003) the following scenarios were defined and analysed to address the uncertainty in the system evolution: Reference Scenario, Climatic Scenario, Deep Well Scenario and Poor Sealing Scenario.

In ENRESA 2003 many variants of the Reference Scenario were analysed using alternative models when there were significant conceptual uncertainties: different canister durations, constant spent fuel matrix alteration rate instead of the alpha radiolysis model, simultaneous failure of all the canister instead of failure spread over a long time period,…

In ENRESA 2003 data uncertainty is explicitly included in the probability distributions used in the probabilistic calculations.

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5. *How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.*

The treatment of uncertainties is so far very limited in scope. Safety Assessments have been performed for synthetic sites, created on the base of limited data available for the Spanish favourable areas. Due to the lack of a real site, data must be taken from the literature or be based on the limited information obtained during the site searching programme. This leads in general to defining wide ranges of values for most host rock parameters, to cover the different potential sites.

Near field barriers are better defined in the preliminary repository concepts. Although R&D programmes have already provided a significant amount of data, much uncertainty remains due to the open decisions on the final design and the fitting to the geological environment. As a consequence, for the near field models an enlarged range of data taken from the bibliography has been adopted, leading also to quite wide ranges of values of near field parameters.

Example: Bentonite is considered as buffer material in the disposal drifts for the Spanish repository concepts in granite and clay. On the base of bibliographic data, small ranges were assigned to the diffusion accessible porosities of bentonite, narrow ranges were assigned to the pore diffusion coefficients (Dp) and much greater ranges (up to several orders of magnitude) to the distribution coefficients of many chemical species.

Taking into account the stage of the Spanish programme, great uncertainties are judged unavoidable, but this has a beneficial effect, because the large uncertainty ranges considered ensure that potential combinations of parameter values that would lead to high doses can be identified. Uncertainties will be reduced at later stages when site specific information become available and engineered barriers properties are better known.

Since generic synthetic sites are used in Spanish Safety Assessments there are significant uncertainties regarding the future evolution of the system, which is analysed through different scenarios. Covering a wide spectrum of future evolutions is useful at the current stage of the Spanish programme because it provides information that can help for site selection. At later stages, when a site becomes available, the number of potential future evolutions of the system can be reduced.

Due to limitation in knowledge, there can be different alternative conceptual models to represent a given process. To deal with this uncertainty, calculations are performed with the different models in order to identify their relevance for the global system (for instance, two alternative models of matrix alteration are considered: time decreasing matrix alteration due to alpha radiolysis and a small constant alteration

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rate in reducing conditions in presence of H_2). Hopefully, progress in scientific knowledge will allow to select the right model, and decrease the model uncertainty.

6. What approach to system Performance Assessment is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?

In Spanish Safety Assessment exercises the probabilistic approach is preferred, although deterministic calculations are performed too, taking the best estimate (most likely) values for the latter. Then, deterministic calculations may be considered realistic in general, but for uncertain favourable processes which, in general, are not considered (for example: the hindering by hydrogen build up of radiolytic spent fuel matrix oxidation is ignored)

Deterministic calculations are performed using highly detailed codes. The calculation chain is formed by a set of individual calculations with manual transfer of the results from one code to the next one. As a consequence, a complete deterministic calculation can take several days and requires a significant human effort.

Probabilistic calculations allow including explicitly the parameter uncertainties in the calculations. In addition, all the models used in the global calculation are implemented in a single input file for computer code (GoldSim) and a calculation requires little human effort.

The self-contained probabilistic models, together with the fast algorithms used in GoldSim allow performing many calculations in a short time period. As a consequence, sensitivity and uncertainty calculations are performed following the probabilistic approach.

The consistency between probabilistic and deterministic approaches has been verified at a general, informal level.

For the reasons exposed (less human effort and treatment of parameter uncertainty) the probabilistic approach is preferred, nevertheless the deterministic approach is judged also necessary, as it allows a more detailed and rigorous representation of the processes and of the geometry of the system.

7. How does the Performance Assessment conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.

The purpose of the sensitivity analysis is to understand how the system works and which parameters have a strong influence on results (mainly doses) and which are less relevant. This sensitivity analysis is performed through a set of parameter

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variation and "what-if" calculations. In the parameter variation calculations values are changed by a small factor, while in the "what-if" calculations radical assumptions are usually made (no solubility, no sorption,…) leading to much greater parameter changes.

Uncertainty analysis is understood as the quantification of the effect of the uncertainties in the assessment bases on the system performance indicators (essentially individual dose). This is being done through probabilistic assessment.

The previously identified three classes of uncertainties are treated in the PA in different ways:

- calculations are performed for several scenarios in addition to the Reference Scenario.
- probabilistic calculations are performed using alternative models when there are significant conceptual uncertainties (i.e. alternative fuel alteration models,…).
- parameter uncertainties are included in the probability distributions used in the probabilistic calculations, allowing to transmit the uncertainty to the results (doses).

In the Safety Assessments already performed by Enresa a limited post-processing of the probabilistic results has been done: only mean doses and percentiles have been used. No formal analyses of which parameters control the uncertainties in the results have been done, but it is considered an interesting topic for the future.

8. What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.

Spanish Safety Assessment exercises for repositories in granite and clay were done assigning wide ranges of values to most parameters, and doses were found to be well below the acceptance criteria. None of the individual runs of the probabilistic calculations leads to doses greater than 3% of the reference value (1E-4 Sv/yr).

We think that the previous result is a strong argument to show that there is no potential combination of values of the uncertain parameters that could lead to unacceptable results, and no efforts to further reduce uncertainties are necessary. This may be satisfactory for the current stage of feasibility studies. Nevertheless in future stages, in particular when the safety authorities and the public opinion need to be confronted and comforted, this is not enough. We think that it will be necessary to demonstrate that a strong scientific base is available, that the uncertainties are identified and properly managed, and that every reasonable effort to reduce them has been made (this would be a very long and gradual process, extended to he whole

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development process, until the final closure, and probably beyond).

9. What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.

Uncertainty management is intimately linked to the issue of confidence. The main element is the existence of a sound scientific programme subject to QA principles. The progress in terms of scientific understanding and data shall have to be submitted to critical analysis at different levels (assessment team, collaborating experts, overview groups, peer reviews, safety authorities). The step by step processes also plays an important role here, as the long time frames assure that new people come in and have a fresh look to the different issues. The third aspect is the robustness of the system (this mean that the system is a) reasonably predictable and b) forgiving in case of deviation, i.e. not very sensitive to uncertainties). Regarding the formal uncertainty analysis, both methodological approaches and mathematical methods are of fundamental importance.

10. What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?

Since no site has been selected in the Spanish programme, there are great uncertainties in all geosphere data. Uncertainties in near field barriers are smaller, but remain significant.

The Safety Assessment exercises for repositories in both granite and clay rock were done assigning wide ranges of values to most parameters, and doses were found to be well below the acceptance criteria. None of the individual runs of the probabilistic calculations leads to doses greater than 3% of the reference value (1E-4 Sv/yr).

In the future, when more data (mainly site specific) become available, uncertainty ranges are expected to decrease but remain bounded by those already used. Doses will be bounded by the estimates already performed too. As a consequence, we do not think that uncertainties could jeopardise the project in future stages of development.

Up to now, none of the uncertainties considered jeopardize the acceptability of the repository.

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Date:	January 9th 2007

11. How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.

Uncertainty and sensitivity analyses have been very useful to identify the processes and parameters that control the long term repository evolution and its capability to isolate the radionuclides and delay their transport.

These methods have allowed to rank the importance of radionuclides , processes and parameters for the performance of the repository system. For instance, in the transport in the near field of a repository in granite it has been identified that for most radionuclides the main parameters are the distribution coefficients (Kd) and the equivalent water flow in the granite (Q_F), while the importance of the other parameters (Dp and θ and solubility limits) is in general much smaller. Obviously these results are radionuclide-specific.

12. What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.

Enresa has practically no experience on this subject and we believe that the best way is to follow a systematic approach, identifying explicitly each type of uncertainty (3 types in the Enresa case) and how has been treated each one in the Safety Case.

13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

We, as users of probabilistic approaches, think that an important weakness is the definition of pdf's. We think this is an important field for improvement, and it is one of the reasons why we proposed a task on expert judgement elicitation. At a general level, in our opinion the methods to define pdf's are of high priority.

The development of a methodology to extract as much information as possible from the fully probabilistic calculations would be useful. In particular, a systematic approach to identify the parameters that control the uncertainty in the results (doses) would help to focus R&D efforts. In the past, Enresa took place in the NEA PSA Group, and sustained an important activity in that area, which led to the proposal of a large number of sensitivity methods. Nevertheless, they did not prove to be very useful in safety assessment exercise. We think it is important to have a new verification of the potential usefulness of those, or new sensitivity analysis methods.

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Another area which in our opinion needs developments is the change of scale. This is in particular the case for the modelling of the far field, especially in the integrated performance assessment, where parameter values for coarse models must be selected on the base of field data.

At a very high level, we think it would be very interesting to delineate an integrated and consistent view on the way to implement an appropriate management of uncertainty and how to show it: requirements, methods and tools.

14. Any other comments?

No

15. What are the key references that support your response?

Enresa response is based on the Spanish Safety Assessments exercises for spent fuel repositories in granite (ENRESA 2000) and clay (ENRESA 2003). Both documents are available only in Spanish.

A12 Sweden - SKB

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	SKB
Responsible Person(s):	Allan Hedin
Date:	2007-01-11

1. *What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?*

Detailed site characterisation stage, see section 1.1 of SKB TR-06-09 for more details.

2. *What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?*

See response from SKI.

3. *How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.*

All responses below are based on experiences and results from the SR-Can safety assessment project, the main report of which, SKB TR-06-09, was published in November 2006.

Several reports produced in the SR-Can project, with their **names in bold**, are referred to below. All these are primary references of central importance for the assessment and are published together with the SR-Can main report. See further the SR-Can main report, SKB TR-06-09 section 2.2.1, for a complete list of, and full references to these reports.

In SR-Can, the following broad definitions/classifications are used.

System uncertainty 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?

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.

Data uncertainty concerns all quantitative input data used in the assessment. There are a number of aspects to take into account in the management of data uncertainty.

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These include correlations between data, the distinction between uncertainty due to lack of knowledge (epistemic uncertainty) and due to natural variability (aleatoric uncertainty) and situations where conceptual uncertainty is treated through a widened range of input data. The input data required by a particular model is in part a consequence of the conceptualisation of the modelled process, meaning that conceptual uncertainty and data uncertainty are to some extent intertwined. Also, there are several conceivable strategies for deriving input data. One possibility is to strive for pessimistic data in order to obtain an upper bound on consequences in compliance calculations, another option is the full implementation of a probabilistic assessment requiring input data in the form of probability distributions. These aspects are further discussed in a dedicated **Data report**, an important reference for the SR-Can assessment.

4. *How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.*

There is no clear distinction between a quantitative PA and a wider safety case in SR-Can. All relevant calculations are seen as part of the safety case. The following can be said about the treatment of different kind of uncertainties:

<u>System uncertainty</u>

System uncertainty is generally handled through the proper management of FEPs in the SR-Can FEP database according to the established routines described in the SR-Can **FEP report**. The database structure and FEP management routines have been set up to assure that the following information is obtained:

- A sufficient set of initial conditions. This is obtained by including all initial state FEPs in the database. These are, however, often formulated in general terms and have to be expressed in a way that is specific to the KBS-3 system. This is done through the systematic documentation of a reference initial state in accordance with the description in the **Initial state report** and by using that reference initial state as a starting point for alternative initial states.

- A sufficient set of internal, coupled processes. This is obtained by including in the assessment all relevant process FEPs in the database. It is important to note that the database already from the start includes the result of several earlier exercises aiming at process identification for the KBS-3 concept. Influences between processes are handled, in the **Process reports**, by systematically going through a set of defined physical variables that could mediate influences and by the systematic treatment of boundary conditions for each process. Hence, in addition to including FEPs describing influences and couplings, the procedures for process documentation are set up in a way that enforces a systematic search for such

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influences.

- A sufficient set of external influences. This is obtained by including in the assessment all relevant external FEPs and by structuring the documentation of these in the **Climate report** in a format similar to that used for the internal processes.

Scenario selection

Another aspect of system uncertainty concerns 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.

Conceptual uncertainty

The handling of conceptual uncertainty for internal processes is essentially described in the **Process reports**. For each process, the knowledge base, including remaining uncertainties, is described and, based on that information, a handling of the process in the safety assessment is established. Alternative conceptual models are sometimes formulated, and of these the model yielding the highest consequences is frequently chosen for compliance canlculations. (Uncertainty regarding influences between processes can be seen as either system uncertainty or conceptual uncertainty, it is described as system uncertainty above.)

Through the use of a defined format for all process descriptions, it is assured that the processes and their associated conceptual uncertainties are described in a consistent manner. External reviews of central parts of the process documentation have also been performed.

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Conceptual uncertainty for external influences is handled in a more stylised manner, essentially through the definition of a sufficient set of scenarios and by using state-of-the-art models for the quantification of external influences, e.g. ice models for the modelling of glacial cycles. Another method is the use of bounding cases that ensure that the consequences are overestimated.

Data uncertainty

Data uncertainties are handled according to established routines described in the **Data report**.

Quality assurance is obtained through the use of a template for data uncertainty documentation, through clearly defined roles for participating experts and generalists and by the use of external reviews prior to finally establishing input data for the assessment.

Modelling

An essential part of the assessment concerns the quantification of both repository evolution and dose and risk consequences through mathematical modelling. Apart from requiring appropriately defined models that represent relevant conceptualisations of the processes to be modelled and quality assured input data, this step requires:

- good model documentation, including results of code verification and results of benchmarking against other models;
- procedures to detect and protect against human error in the execution of the models.

A dedicated SR-Can **Model summary report** describes models used in the assessment and provides references to more detailed descriptions of the models. Mapping of processes to models, provides an overview of the models used. A guiding principle is that models and data should be documented in sufficient detail to allow calculations to be reproduced and audited.

Human errors can be prevented e.g. by formal procedures for checking that input data are correct and by the use of alternative, often simplified, models for crucial aspects of quantification. An example of the latter is given in calculations of radionuclide transport and dose.

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5. *How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.*

No general answer can be given to such a question.

For each process of importance for long-term safety, a treatment in the safety assessment is established based on the available knowledge following a pre-defined template, see section 6.3 of SKB TR-06-09 for an introduction. Numerous examples are provided in the SR-Can **Process reports** SKB TR-06-18, TR-06-19, TR-06-22 and TR-06-23.

Not only the level of knowledge dictates the treatment, but also the importance of the uncertainty to safety. For example, the longevity of the fuel cladding is uncertain, but this is in most situations not important for safety. Therefore, the barrier function of the cladding is disregarded.

6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?*

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.

This is partly controlled by regulatory requirements. The primary compliance criterion is a risk limit, requiring some kind of probabilistic approach, see further section 2.9 of SKB TR-06-09. However, it is also a requirement that the assessment results are presented in a disaggregate fashion so that main risk contributors can be clearly identified.

7. *How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.*

Sensitivity analysis is in SR-Can generally understood as a determination of how sensitive a certain calculation endpoint is to variations in input parameters. For example, several hydraulic interpretations of a particular site were provided from the site modelling. Each of these gave different input distributions of hydraulic parameter for radionuclide transport calculations. A separate Monte Carlo calculation was done for each interpretation, but it was not possible to assign probabilities to the different interpretations. This is thus an example of an analysis of sensitivity of dose consequences to different hydraulic interpretations. This and several other examples are documented in section 10.5.7 in SKB TR-06-09. See also

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the discussion in section 10.11.

Sensitivity analysis may also be understood as the process of assigning, to uncertain input variables, a measure of importance with respect to a resulting calculation endpoint, e.g. through rank correlations. This is briefly discussed in section 10.5.10, subheading "Sensitivity analyses".

Uncertainty analysis is understood as the quantification of output uncertainty when input uncertainty has been quantified, usually by means of Monte Carlo calculations with given input distributions. For example, the results of the probabilistic base case calculation in Figures 10-16 and 10-17 in SKB TR-06-09 quantifies the uncertainty in annual dose for the input distributions given in Table 10-3.

8. What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.

A number of confidence related issues are discussed in section 13.3.5 of SKB TR-06-09.

9. What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.

Essentially methodological approaches to manage qualitative uncertainties, see further response to question 4.

10. What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?

Important examples include:

a. The extent of buffer erosion/colloid release when exposed to dilute groundwaters during glacial conditions.

b. The hydraulic interpretations of the candidate sites.

c. The extent of thermally induced spalling in the host rock near the deposition holes.

Of these, the first, if unresolved, may delay the completion of the current program stage.

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11. *How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.*

See the concluding chapter 13 of the SR-Can main report, SKB TR-06-09. In particular, feedback to canister design, to repository design, to site investigations, to RD&D programme and to future safety assessments is provided in sections 13.5 through 13.9.

12. *What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.*

So far the results have been communicated to regulators and experts. No "best" technique can be identified, but several approaches are used as appropriate, for example:

- Data uncertainty as simple box-and-whisker plots or cumulative distribution functions, see e.g. Figures 9-25 and 9-30 of SKB TR-06-09.
- Output data uncertainty for a particular calculation case as percentiles of dose as a function of time, see e.g. Figures 10-16 and 10-17 of SKB TR-06-09.
- Impact of conceptual uncertainty as comparisons of mean values as a function of time of probabilistic calculation results using different assumptions, see e.g. several Figures in section 10.5.7 of SKB TR-06-09.
- For a distinction between epistemic and aleatoric uncertainty, see SKB TR-06-09, section 10.5.1, first subheading.

In addition, a clear verbal description/interpretation of the results is often more important than the particular technique used when presenting the numerical results.

13. *With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.*

Several aspects of the handling of uncertainty in the SR-Can project can and will be further developed but no particular issues suitable for a cross-programme working group come immediately to mind. (We are not actively planning for participation in RTDC2).

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14. Any other comments?	
No.	
15. What are the key references that support your response?	
Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. Main report of the SR-Can project. SKB TR-06-09, available through www.skb.se	

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1. *What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?*

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

Regarding the repository for SF, HLW and ILW, Project Opalinus Clay (Entsorgungsnachweis[2]) was submitted to the Federal Government at the end of 2002. This feasibility study had the aim to demonstrate that a safe repository for SF / HLW / ILW can be implemented using current technology and that a site with the required properties for construction and for long-term safety exists within Switzerland. After an extensive review process followed by a three-month public consultation phase, the Swiss Government (the Federal Council) announced its approval of the project on 28th June 2006.

In the case of the repository for L/ILW, an advanced project at Wellenberg, Canton of Nidwalden, had to be abandoned on political grounds after the population of the Canton of Nidwalden rejected the plans for the proposed underground investigation gallery in 2002.

Partly as a consequence of this set-back, the Federal Office of Energy is currently defining a site selection process for repositories for all waste categories, which is expected to enter into force in 2007.

The basis for the answers to this questionnaire is Project Opalinus Clay (Nagra 2002a, b, c).

2. *What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?*

The principles and protection objectives that a final repository for radioactive waste in Switzerland must meet are defined in Guideline R-21 (HSK&KSA 1993), issued jointly by the Swiss Federal Nuclear Safety Inspectorate (HSK) and the Federal

[2] This German term translates into English as “demonstration of disposal feasibility”.

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Commission for the Safety of Nuclear Installations (KSA). Three protection objectives are defined:

– **Protection Objective 1**

The release of radionuclides from a sealed repository subsequent upon processes and events reasonably expected to happen, shall at no time give rise to individual doses which exceed 0.1 mSv per year.

– **Protection Objective 2**

The individual radiological risk of fatality from a sealed repository subsequent upon unlikely processes and events not taken into consideration in Protection Objective 1 shall, at no time, exceed one in a million per year.

– **Protection Objective 3**

After a repository has been sealed, no further measures shall be necessary to ensure safety. The repository must be designed in such a way that it can be sealed within a few years.

No time cut-off is specified for post-closure assessments. HSK/KSA suggest that "...dose and risk calculations should be carried out for the distant future, at least for the maximum potential consequences from the repository...". It is however recognised that, in view of uncertainties, dose calculations for the distant future are to be interpreted as indicators, and should be based on the use of " ... reference biospheres and a potentially effected population group with realistic, from a current point of view, living habits ..."

Regarding the treatment of uncertainty in models and datasets, R-21 states:

"When calculating dose or risk, the applicant has to give the possible ranges of variation of the relevant data. He also has to give the range of variation in the results following from these data. Conservative assumptions are to be made, where uncertainties remain. Uncertainties which are due to incomplete knowledge of the properties of the repository system and to incomplete understanding or simplified modelling of release and migration mechanisms have also to be estimated."

There is also a paragraph in R-21 related to optimisation ("safety enhancing measures"):

"Even if compliance with Protection Objectives 1 and 2 is demonstrated, the radiological consequences from the repository have to be reduced by appropriate measures as far as feasible and justifiable with current status of science and technology. However, owing to the uncertainties involved in determining potential

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radiation exposure, no quantitative optimisation procedure is required."

3. How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.

In Project Opalinus Clay, a distinction is drawn between, on the one hand, completeness uncertainty, which can be reduced and to some extent avoided by appropriate FEP management (see Nagra 2002c), but can neither be quantified e.g. in terms of probabilities nor entirely eliminated, and on the other hand uncertainties regarding the evolution and performance of a system which are explicitly addressed in the safety assessment by means of a wide range of assessment cases. These latter uncertainties are in turn classified according to the following scheme:

Scenario uncertainty is uncertainty in the broad evolution of the repository and its environment. This can also be considered as the uncertainty related to inclusion, exclusion or alternative realisations of FEPs that may affect this broad evolution.
Conceptual uncertainty is uncertainty in the assumptions or conceptual model used to represent a given scenario or set of FEPs, including uncertainty related to the existence of plausible alternative conceptual models.
Parameter uncertainty is the uncertainty in parameter values used in a model. Parameter uncertainty can be due to spatial variability and evolution over time of relevant properties and to uncertainty in the extrapolation of observations from laboratory or natural system conditions and scales of space and time to the conditions and scales relevant to the repository and its environment. Parameter uncertainty can also arise from uncertainty in the models used to interpret the raw data used to derive the parameters required for SA.

One example is how the consequences of future human actions were evaluated. First, this was regarded as a separate scenario. Within this scenario the following conceptualisations were considered: (i) a borehole penetrating the repository (near hit, direct hit); (ii) extraction of groundwater from a deep well in an aquifer above the Opalinus Clay host rock; (iii) abandoned repository. These conceptualisations were then evaluated with different parameter sets to assess the effect of parameter uncertainty. See also the figure in the answer to Question 4.

4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

Specific measures to reduce completeness uncertainties in Project Opalinus Clay include:

- the use of international FEP lists as checklists against which to compare the assessment basis, assessment cases and the models used for their evaluation;

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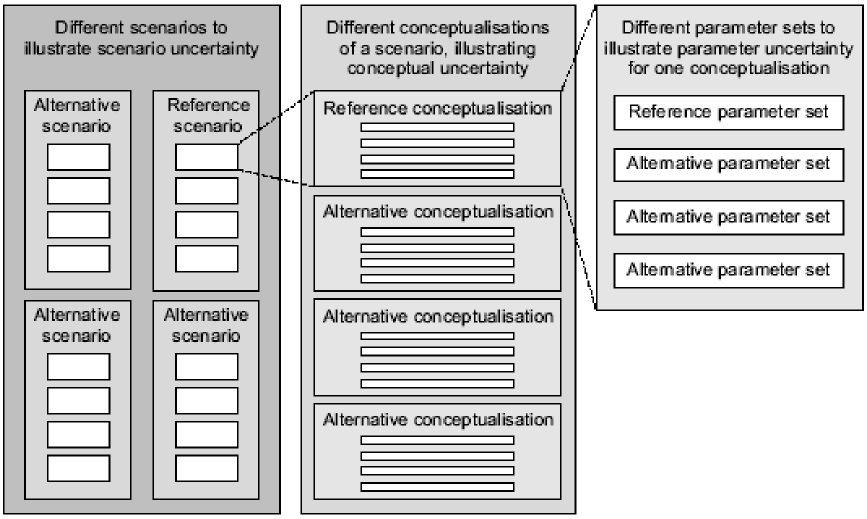
- the systematic consideration of potential interactions between FEPs;

- providing appropriate guidelines, in order to encourage the responsible experts to take into account all relevant sources of information and to consider all possible sources of uncertainty;

- the use of peer review by internationally acknowledged experts for all key technical reports.

As mentioned in the response to Question 3, adhering to certain principles in siting and design can also reduce completeness uncertainty (e.g. designing for simplicity and robustness).

Other uncertainties were treated primarily by defining and analysing a wide range of assessment cases - i.e. specific model realisations of different possibilities or illustrations of how a system might evolve and perform. The cases each address the impact of some particular uncertainty or combination of uncertainties (the insensitivity of a system to completeness uncertainty in some aspects of evolution and performance was also tested in Project Opalinus Clay by means of "what-if?" assessment cases). The categorisation of uncertainties according to the scheme shown in the response to Question 3 provided a basis for organising the cases. Thus, scenarios were represented by groups of individually analysed cases. Within each scenario group, sub-groups of cases addressed alternative possibilities arising from conceptual model uncertainties. Individual cases within each subgroup addressed alternative possibilities arising from parameter uncertainties. This hierarchy of assessment case groupings is illustrated in the following figure (Fig. 3.7-3 in Nagra 2002a):



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Uncertainties in the evolution of the biosphere and future human actions that may change exposure to contaminant releases and that could disturb a disposal facility, being less readily characterised than uncertainties in the evolution of the engineered barrier system and geological environment of a repository, were treated as separate scenarios using a stylised approach (see also answer to Question 3).

Finally, some uncertainties were treated using model assumptions or simplifications that are conservative, meaning that they tend to over-estimate evaluated doses or risks. This approach was used, for example, where there was no adequate model or database to evaluate the impact of a particular FEP, but simply omitting the FEP or treating it in some highly simplified manner was confidently expected to lead to conservative results.

In the safety case for Project Opalinus Clay, it was argued that the outcome of the safety assessment has shown that the remaining uncertainties and open questions that have been identified through a systematic and comprehensive procedure do not put safety in question. Although there are many steps to be taken before a repository is definitively sited in Switzerland, there is ample time to continue investigations that address a wide range of uncertainties and to iterate on the repository design.

An RD&D Plan is currently being developed that takes into account the findings from Project Opalinus Clay and its review.

5. *How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.*

The knowledge base for Project Opalinus Clay includes results from laboratory and field experiments and from observations of natural systems. The most important elements are summarised in Tab. 8.2-1 of the Safety Report Nagra 2002a. This includes in many instances multiple lines of evidence.

The level of knowledge dictates the treatment of uncertainty to the extent that:

- if an uncertainty can be show, e.g. by qualitative argument or sensitivity analyses, to have a negligible impact on system evolution and performance, then it may be possible to disregard it in the definition and analysis of assessment cases (example: effects of corrosion of structural elements in highly compacted bentonite blocks avoided by design, see Tab. 3.4-1 in Nagra 2002c);

- if a potentially significant uncertainty can be quantified - e.g. in terms of upper/lower bounds on a parameter, a probability density function or a set of alternative plausible models or scenarios, and suitable models and databases are available, then its impact can be investigated by defining and

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analysing corresponding assessment cases (example: sorption values on bentonite and on Opalinus Clay given in terms of reference-case values, lower limit, upper limit);

- if a potentially significant uncertainty cannot be quantified because suitable models and/or databases for its analysis are not available, then a conservative or pessimistic approach may be adopted to bound the effect of the uncertainty (example: conservative omission of sorption of radionuclides on canister corrosion products places an upper bound on the effect of this type of uncertainty);

- if a potentially significant uncertainty cannot be quantified, then a stylised approach may be appropriate (example: future human actions).

6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?*

The use of conservatism has been discussed in the response to earlier questions. In general, some degree of (conservative) simplification in assessment modelling is necessary in view of the complexity of the system modelled and the limited understanding of some processes, and in view of the need to produce defensible bounding estimates of consequences. More detailed and realistic modelling of subsets of FEPs is, however, carried out in order to assess the impact of simplifications and to support parameter selection (e.g. use of mechanistic sorption models to support the selection of *Kd*s for assessment models).

The emphasis in Project Opalinus Clay was on the one-by-one ("deterministic") analysis of assessment cases, since these were considered to give a clear illustration of the impact of individual uncertainties and design variations (or limited combinations of these uncertainties and variations) on system performance. Providing guidance regarding key uncertainties that need to be reduced, avoided or their impact mitigated at future project stages was one of the aims of the safety assessment for Project Opalinus Clay.

Probabilistic calculations were, however, also used to explore systematically the consequences of different combinations of parameters that fall within the ranges of uncertainty. Probabilistic calculations were used to enhance system understanding, to ensure that no unfavourable combinations of parameters were overlooked, and to test whether there were sudden or unexpected changes in performance as parameters were varied, which might not have been detected using a deterministic approach.

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7. *How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.*

Sensitivity analyses are explorations of how a modelled system responds to variations in parameter values or model assumptions. In Project Opalinus Clay, sensitivity analyses were performed both deterministically (i.e. with the models and parameter values defining each calculation individually specified by the safety assessor to investigate the impact of particular uncertainties) and probabilistically (i.e. with parameter values randomly sampled from probability distribution functions). One example of a sensitivity analysis is the calculated dose as a function of canister breaching time, which showed that canister breaching time is an insensitive parameter (Fig. 6.7-4 in Nagra 2002a).

Uncertainty analysis is seen as the broader activity of identifying and quantifying uncertainties, and evaluating their potential impacts. As noted earlier, the results of sensitivity analysis can guide the approach adopted to the treatment of specific uncertainties in the safety assessment (see the response to Question 5). Sensitivity analysis is thus a tool used by the broader activity of uncertainty analysis.

8. *What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.*

Supporting arguments (i.e. arguments not directly related to the outcome of the evaluation of assessment cases) that address uncertainties include arguments to support the exclusion from the analyses of uncertainties judged to be irrelevant, and to support the conservatism of the treatment of other uncertainties. As mentioned earlier, such arguments can come from sensitivity analyses. They can also come from qualitative reasoning (e.g. processes such as sorption on waste degradation products can only be beneficial to performance, and so their exclusion is conservative). An example for a line of argument supporting the statement that in Opalinus Clay, diffusion will be the dominating radionuclide transport process, is the existence of measured diffusion profiles of natural tracers in Opalinus Clay, which can be explained by assuming diffusion was the only transport mechanism in the past ~ 1 Ma (see following figure).

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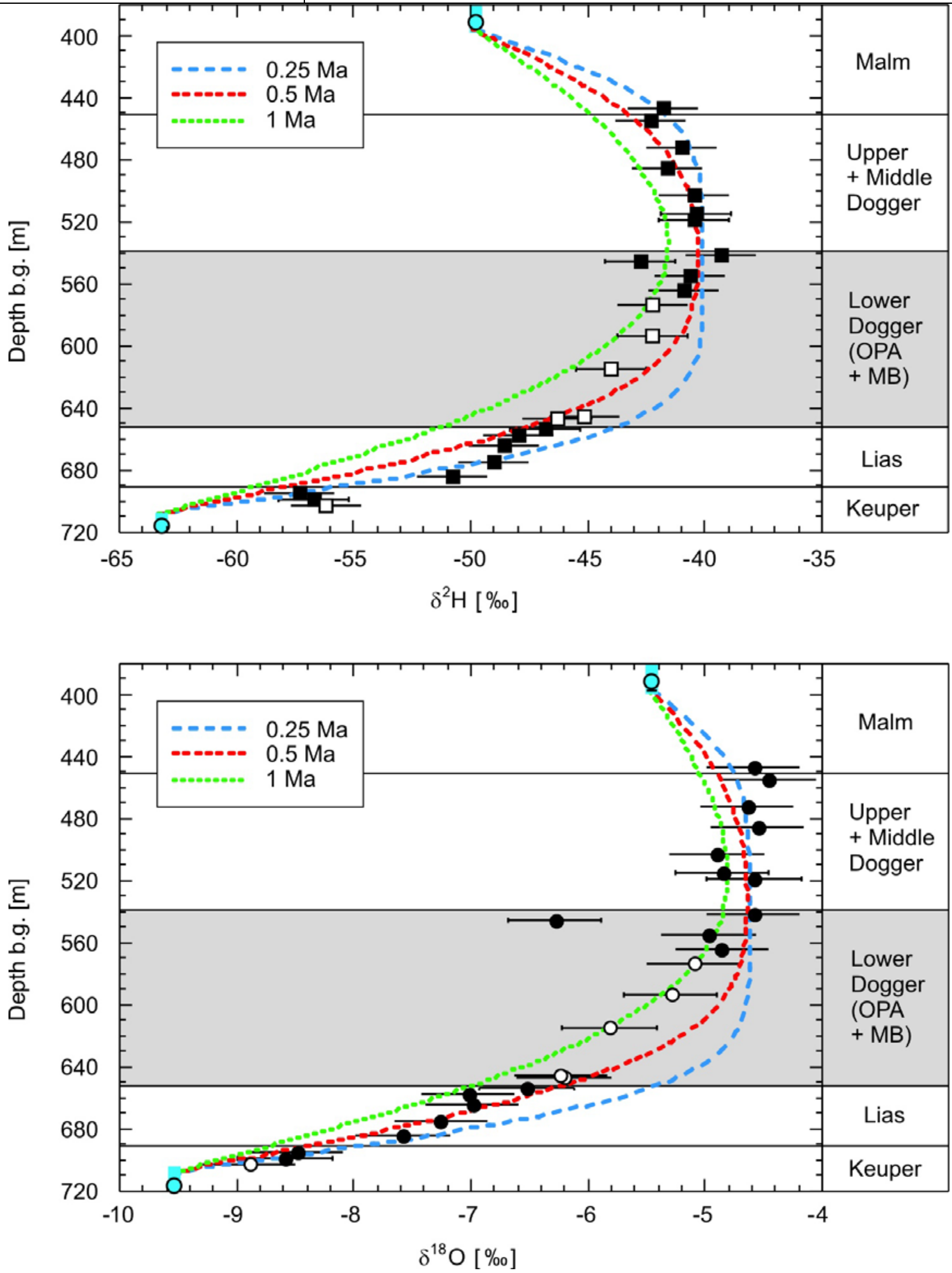

Isotope concentration profiles in porewater across the Opalinus Clay (OPA) and adjacent rock strata due to diffusion that occurred for 0.25, 0.5 and 1 Ma. Taken from Nagra 2002a (Fig. 4.2-14).

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The existence of reserve FEPs - i.e. FEPs that are considered likely to occur and are beneficial to safety and are deliberately and conservatively excluded from quantitative analysis because suitable models and / or databases are unavailable - constitutes a complementary qualitative line of argument enhancing confidence in long-term safety. An example for a reserve FEP is the delayed release of radionuclides from corroding metallic materials in the ILW (all radionuclide releases from ILW were treated as being instantaneous).

Another line of argument is that remaining potentially important uncertainties not comprehensively addressed in the safety assessment are "under control", meaning that there is an adequate strategy to address them, e.g. by further RD&D during future stages. It is pointed out in the Project Opalinus Clay safety report that it is not possible, nor is it necessary, to eliminate uncertainties completely in order to make a safety case that is adequate to support a positive decision to proceed to the next programme stage.

9. What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.

Measures include those adopted to promote completeness (see the response to Question 4), siting and designing the repository according to principles such as robustness and simplicity with the aim of reducing uncertainties and their impact, and measures to promote the quality of the analyses (e.g. through the prevision of systematic reviews of work and reports, validation of models and databases, verification of computer codes, reliable and traceable procedures for running the codes, etc.). Design and assessment principles are given in Tabs. 2.6-1 and 2.6-2 in Nagra (2002a). The QA measures applied throughout Project Opalinus Clay are summarised in Appendix 8 in Nagra (2002b).

10. What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?

In Project Opalinus Clay, it was found that uncertainties in the initial characteristics of the disposal system are relatively small (with the exception of some alternative system or design options). Key uncertainties concern mainly the rates of processes affecting the evolution of the engineered barriers and a range of phenomena that may perturb the geological setting and, in particular the impact of repository-generated gas, which is not readily transported in this particular host rock. The highest calculated doses arose in scenarios illustrating the release of radionuclides affected by human actions. Project Opalinus Clay concluded that, despite an analysis of a wide range of assessment cases that was derived in a careful and methodical way, the safety assessment did not identify any outstanding issues or uncertainties with the potential

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to compromise safety.

11. *How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.*

One of the important results of the safety assessment for Project Opalinus Clay, including the associated uncertainty analysis, was the identification of features of the disposal system that are key to providing long-term safety. These features, which include, for example, the *host rock*, which has a low hydraulic conductivity, a fine, homogeneous pore structure and a self-sealing capacity, thus providing a strong barrier to radionuclide transport and a suitable environment for the engineered barrier system, are termed the "pillars of safety". Although the pillars of safety are already considered well understood, a conclusion of the project was that further understanding of phenomena directly related to their evolution and performance will strengthen future iterations of the safety case.

12. *What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.*

In communicating the different types of uncertainties, it was found useful to have developed, as part of the safety case, a clear strategy for the evaluation and treatment of uncertainties, including a definition of the different types of uncertainties (see answer to Question 3). In explaining this strategy, the figure shown in the answer to Question 4 worked quite well. To illustrate with a few selected examples how the effects of uncertainties were evaluated within the scheme shown in that figure, the following figure was found useful (Fig. 5.7-1 in Nagra 2002a):

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Responsible Person(s):	J. Schneider
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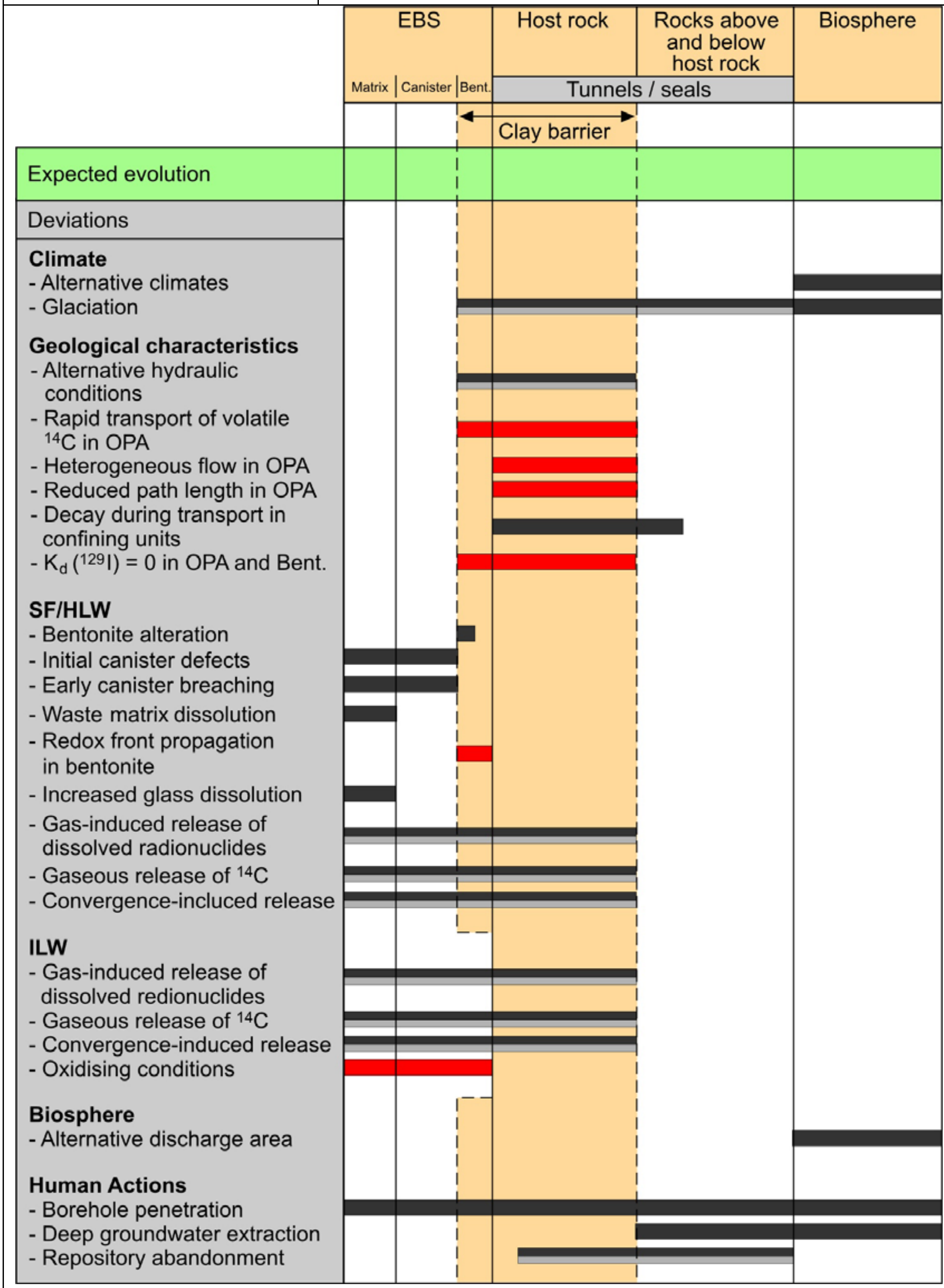

Range of influence of possible deviations from the expected evolution of the disposal system (Fig. 5.7-1 in Nagra 2002a). Black bars – transport through host rock, gray bars – transport through tunnels/ramp/shaft and seal system, red bars – "what if?" cases.

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Responsible Person(s):	J. Schneider
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13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

This question is biased: It implies that it is clear that there are gaps of understanding of how uncertainty should be treated. In Project Opalinus Clay, it was claimed that the treatment of uncertainties was adequate for the project stage.

14. Any other comments?

15. What are the key references that support your response?

HSK & KSA (1993): Protection objectives for the disposal of radioactive waste, HSK-R-21/e. Swiss Federal Nuclear Safety Inspectorate (HSK) and Federal Commission for the Safety of Nuclear Installations (KSA), Villigen-HSK, Switzerland.

Nagra (2002a): Project Opalinus Clay: Safety Report. Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Nagra Technical Report NTB 02-05. Nagra, Wettingen, Switzerland.

Nagra (2002b): Project Opalinus Clay: Models, codes and data for safety assessment. Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Nagra Technical Report NTB 02-06. Nagra, Wettingen, Switzerland.

Nagra (2002c): FEP management for the Opalinus Clay safety assessment. Nagra Technical Report NTB 02-23. Nagra, Wettingen, Switzerland.

A14 United Kingdom - Nirex

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Organisation(s):	Nirex
Responsible Person(s):	Mike POOLE
Date:	27 November 2006

1. What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?

In the UK there has recently been a period of consultation regarding the options for long-term radioactive waste management, undertaken on behalf of Government by an independent Committee on Radioactive Waste Management (CoRWM). It was the recommendation of CoRWM to implement deep geological disposal, and this recommendation has now been endorsed by the Government. In the mean time, in order to be able to continue to provide advice on the conditioning and packaging of wastes to waste producers, Nirex has developed a generic phased geological repository concept. This questionnaire is answered with respect to this concept, i.e. a generic viability study.

2. What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?

In the context of the long-term safety of a deep radioactive waste repository in the UK, the Environment Agency, in conjunction with the Scottish Environment Protection Agency and the Department of the Environment for Northern Ireland, published Guidance on Requirements for Authorisation (GRA) [1] in 1997. This replaced earlier advice published in 1984 and sets out guidance on the principles and requirements against which the Agencies and associated regulatory authorities would assess any application for authorisation under the Radioactive Substances Act 1993 for the operation of a waste repository.

The GRA includes a set of four principles and eleven requirements covering all aspects of the design, construction, operation and closure of a deep waste repository in the context of long-term safety. Of most interest are the following:

Requirement R1 is applicable in the period of regulatory control over the disposal site, lasting at most a few hundred years. It states:

'In the period before control is withdrawn, the effective dose to a representative member of the critical group from a facility shall not exceed a source-related dose constraint. Also during this period, the effective dose to a representative member of the critical group resulting from current discharges from the facility aggregated with the effective dose resulting from current discharges from any other sources at the same location with contiguous boundaries shall not exceed an overall site related

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dose constraint of 0.5 mSv yr^{-1}'.

The GRA goes on to state that the Government accepts the NRPB's advice that the source-related dose constraint should not exceed 0.3 mSv yr^{-1}. In common with practice for controlling discharges from operating nuclear facilities, the concept of a critical group is identified.

Requirement R2 is applicable in the period after a repository has been operated and sealed and control is withdrawn. It states:

'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 the risk target of 10^{-6} per year ...'

This requirement introduces the concept of a potentially exposed group. Noting that this is more appropriate than the critical group in the context of long-term potential exposures, an exposed group is defined in the GRA as:

'... any group of members of the public within which the exposure to radiation is reasonably homogeneous: where the exposure is not certain to occur, the term potentially exposed group is adopted'.

Although the main emphasis in Nirex's assessments of the groundwater pathway has been on Requirement R2, consideration is also given to issues relevant to Requirement R5, which states:

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

UK regulatory guidance [1] specifies, 'The developer should … present the range of possible doses which each potentially exposed group may receive, together with the probability that the group receives any given dose.' The regulatory guidance also states the requirement to consider 'all situations that could give rise to exposure' and Nirex has tended to fulfil this requirement by conducting probabilistic assessments and by considering a range of scenarios.

3. *How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.*

The main uncertainties identified by the Nirex post-closure safety assessment team in Nirex's Generic post-closure Performance Assessment (GPA) [2] are as follows:

- Data uncertainty: near-field solubility, near-field sorption, effect of organic complexants on solubility and sorption, far-field sorption, inventory, biosphere factors, groundwater travel time, groundwater flux through

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repository.

- Model uncertainty: gas generation and migration, waste container corrosion, groundwater pathway models.

- Scenario uncertainty: evolution of the near field, criticality events, evolution of geosphere and biosphere (e.g. climate change).

- Uncertainty regarding human behaviour: start of post-closure period, human intrusion.

This assessment does not use a timeframes presentation, nor does it 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 hence it is proposed that future assessments, based on a timeframes presentation, may use a more sophisticated treatment of the time-variation of parameter values, rather than treating time variation within parameter uncertainty.

4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

Strategies for handling uncertainty tend to fall into the following broad categories:

1. 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.

2. Addressing the uncertainty explicitly, for example using probabilistic techniques.

3. Bounding the uncertainty and showing that even the bounding case gives acceptable safety.

4. 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).

5. Explicitly ignoring uncertainty or agreeing a stylised approach for handling an uncertainty (for example the ‘reference biospheres’ approach developed by the IAEA BIOMASS project).

The preferred treatment of a particular uncertainty will depend on the context of the

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assessment. To build confidence in the safety case, the treatment of uncertainty should aim to be as rigorous as possible. For example, it may be possible to argue that a nuclear criticality incident is very unlikely to occur (strategy 4 above), but if it can also be shown that even if such an incident did occur there would be no significant impact on safety (strategy 1), this is a more robust position, which should lead to greater confidence. In a PA, Nirex uses a combination of these strategies to manage the different types of uncertainty.

See also answer to question 6.

5. *How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.*

A key driver for a deep geological repository as an option for the long-term management of radioactive waste, is to remove the large uncertainties associated with leaving the waste accessible to humans over very long timescales. This is because there is substantially more uncertainty over the future of society than there is over whether the geosphere will perform its desired role of isolating the waste from such future societies. This is reflected in the relative timescales of geological change versus social change.

There is considerable confidence that a well-chosen geological site will be relatively stable for a long time into the future and provide continuing safety from the radioactive material. However, it is also important to recognise that there is substantial uncertainty associated with certain events and processes operating in a radioactive waste repository system on a timescale of a million years or more. Therefore the treatment of that uncertainty is an essential part of a performance assessment to show that, although the uncertainty in some processes may be acknowledged to be large, actually it can be shown that it is acceptable i.e. despite substantial uncertainty a strong safety case can be made.

There is insufficient knowledge about the some of the uncertainties to avoid the need for expert judgement when handling uncertainty in performance assessments. Systematic frameworks and modelling processes provide tools to help the experts, but there will still be situations where judgements need to be made. Expert judgement plays a key role in handling data uncertainty and may be combined with the available empirical data to elicit a full data set or manage the consequences of uncertainty associated with the available data.

Expert judgement is based on scientific/technical understanding and experience, supplemented with appropriate evidence. However, there is still scope for different experts to have different views and for two groups to reach different conclusions regarding an elicited data set, even when they are both using the same empirical

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evidence. Ideally such a situation, if it occurred, should be resolved by discussion between the experts, or with an independent third party if necessary. Disagreement between experts can be one of the main reasons for undermining public confidence in any decision-making process. This emphasises the importance of peer review throughout the performance assessment process and the value in maintaining flexibility in the modelling process to allow the testing of alternative view-points. Where there is more than one expert view, it may be best to conduct two parallel sets of calculations to determine the relative impacts of the conflicting views.

In documenting a performance assessment it is important to ensure that all data and model inputs are traceable. This will mean being clear on the extent and role of expert judgement, for example recording all expert input in an appropriate database that can be easily linked to the models generated, thus creating an audit trail for the impact of such judgements.

6. What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?

In the main, Nirex adopts a probabilistic approach to system PA. This is influenced by the regulatory requirement to identify risks from different repository evolution scenarios and ensure that risks to an individual are summed over all relevant situations.

Nirex considers that the possible evolution of a repository system can be addressed in terms of the following:

- a base scenario that provides a broad and reasonable representation of the natural evolution of the system and its surrounding environment (i.e. includes all those FEPs that are considered more likely than not to persist for a significant part of the assessment period); and

- a number of variant scenarios that represent the effects of probabilistic events (i.e. those FEPs which may or may not occur).

Any FEPs not considered within the base scenario must either be screened from the assessment basis (with a justification for their irrelevance or insignificance) or considered within a variant scenario. Consideration within a variant scenario does not necessarily imply explicit representation of a specific FEP, many FEPs have a similar impact on system performance.

The base scenario is assumed to have a probability of unity. Variant scenarios are assumed to occur with a probability of less than unity. In calculating combined risks from the base and variant scenarios, the conditional risk from the base scenario is

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assigned a weight of unity and the conditional risks associated with the variant scenarios are assigned weights of less than unity. Note, there is no requirement to ensure that the total probability of all scenarios sums to unity, hence the preference for the term ‘weight’ rather than ‘probability’. It is noted, that this in itself, will lead to a conservative estimate of the overall risk.

The scenarios approach leads to an understanding of what is important in terms of the performance of a repository system and hence allows resources to be focused on those aspects most important to safety.

In previous studies screening of scenarios has been carried out using expert judgement on the basis of certain scenarios being physically unreasonable or having an insignificant impact. In order to make such judgements it is necessary to have a suitable framework to ensure that a consistent view is taken in the decision-making process.

In the Nirex approach, the methodology of subsuming replaces that of screening. (Although where a scenario is considered to be immaterial to the system performance it will be regarded as screened from the assessment basis; and individual FEP influences may be screened within the conceptual model development process.) The overall aim is to apply a principle of caution to subsume scenario representations at the highest possible level (for example, into the base scenario whenever appropriate) and hence to treat explicitly only those scenario representations which cannot be subsumed. All subsuming decisions are based on the principle of caution, while reserving the option to revisit a decision if it becomes too onerous. This philosophy has the advantage of making the assessment tractable and focusing effort on the most important areas in terms of safety implications. All subsuming decisions must be fully justified and will form part of the auditable record of the assessment.

Subsuming of scenario representations involves considering a specific scenario representation in relation to a more general case. If the specific scenario representation has a conditional risk which is similar to or lower than the general case it can be subsumed into the general case. For example, any variant scenario with a conditional risk less than or equal to the base scenario can be subsumed into the base scenario. This will always be conservative, regardless of the probability of occurrence for the variant scenario, as the base scenario is taken to have probability one.

Uncertainties in data can be quantified in terms of ‘probability density functions’ (PDFs) that give the relative likelihood of different parameter values. The PDFs can be based solely on measured values, or, more usually, are generated at a formal elicitation in which measured values are supplemented by the judgement of suitably qualified and experienced experts on the basis of various research data, and can take

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into account any scarcity of data, uncertainty or bias from measurements.

With the uncertainty quantified as PDFs, a probabilistic assessment can be carried out using Monte-Carlo methods. In such an assessment, a computer model is run many times (each run is called a realisation) with different sets of parameter values. In each realisation, the values of the parameters are chosen at random from the PDFs representing the range of possible values. This is a probabilistic approach and it ensures that wide ranges of possible parameter values are considered within a performance assessment. Statistical analysis of the results of a probabilistic calculation can be used to explore the sensitivity of the performance measure e.g. risk to the uncertain model parameters.

The probabilistic approach is also consistent with current regulatory guidance in the UK, as an important regulatory requirement is the calculation the expectation value of risk for comparison with the regulatory risk target. The expectation value of risk is obtained by averaging the calculated risk from each probabilistic realisation.

The probabilistic approach is used to address most of the uncertainties in Nirex's post-closure assessments of the radiological risk from the groundwater pathway.

The challenge is then to be able to communicate this understanding of the relative impact of the uncertainties in a transparent manner. It is often helpful to include other presentations e.g. deterministic sensitivity studies and 'What if?' calculations to improve the understanding and communication of the results of a performance assessment.

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.

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7. How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.

The probabilistic approach ensures that many possible combinations of model parameters are considered; it is therefore a key approach to treating uncertainty in post-closure assessments. However, it is sometimes helpful to consider variations in a particular parameter systematically in order to understand the impact it has on long-term safety. This can be achieved by conducting deterministic sensitivity studies. From a modelling point of view, a deterministic calculation is one that takes fixed parameter values and is run once only, as opposed to a probabilistic calculation which takes sampled parameter values and is run many times. A series of deterministic calculations is usually carried out as part of a sensitivity study with the values of a number of key parameters varied systematically within their uncertainty range. A 'matrix' of calculations are carried out so that the effect of the different values for the different parameters in combination can be investigated. For example, if four parameters are varied, each taking one of two values (a high value and a low value) then 16 (2×2×2×2) calculations would be carried out in total.

The impact of parameter uncertainties on consequences can be demonstrated by comparing a calculation with best estimates for particular parameters with worst case estimates. In this context, a worst case estimate usually means that a parameter is given the worst credible value i.e. there is a low probability of the actual value being worse. 'What if?' calculations can be carried out to investigate the effects of specific values of some parameters. Conceptual model uncertainty can also be addressed in this way, by performing 'What if?' calculations for a small number of alternative conceptual models for the system i.e. to ascertain whether the uncertainty matters.

8. What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.

Generally, a performance assessment will include a range of quantitative performance indicators, together with alternative lines of reasoning and qualitative considerations, such as the intrinsic quality of the repository design, to build understanding in the overall repository performance and hence determine whether it satisfies the relevant safety requirements.

Qualitative arguments can include:

- Comparisons with natural analogues, i.e. occurrences of materials or processes which resemble those expected in a proposed geological waste repository, for example the Maqarin site in Jordan which provides a natural analogue for a cementitious repository.

- Showing consistency with independent site-specific evidence, such as

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observations in nature or palaeohydrogeological information.

- Evidence for the intrinsic robustness of the repository system, for example demonstrating that relevant features and processes are well understood, often supported by evidence from underground research laboratories.

- Describing the passive safety features of the repository and demonstrating that the design uses best practice scientific and engineering principles.

- The safety case may also include more general arguments related to radioactive waste management, and information to put the results of performance and safety assessments into perspective. For example, for the Nirex concept a repository at a depth below ground of about 650m is assumed. Such a depth offers a number of benefits to the long-term management of radioactive waste that would be of relevance to the safety case.

There is also a role in many performance assessments for semi-quantitative arguments, for example applying physical and chemical understanding of the system to build more simple models to give an insight of repository system behaviour.

Qualitative arguments may be particularly important in performance assessments conducted at the earlier stages of a repository development programme. At these stages the focus is on building understanding of the processes that could affect the performance of a repository and on explaining how the repository concept will be able to provide safety over very long time periods. There may also be insufficient data at this stage to justify complex calculations, therefore other methods are required to build confidence in the viability of the proposals. Assessments at this stage are also more likely to be communicated, at least in summary form, to wider, non-technical audiences for whom qualitative arguments may be more meaningful than detailed, complex calculations.

A safety case contains a number of different elements, and is an integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of a radioactive waste management facility. A performance assessment in support of a safety case will include a range of quantitative performance indicators, together with alternative lines of reasoning and qualitative considerations, such as the intrinsic quality of the repository design, to build understanding in the overall repository performance and hence determine whether it satisfies the relevant safety requirements.

Information crucial in the safety case relates to:

- Arguments for groundwater-flow predictability.

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- Retention of potentially released radionuclides

- Predictability of groundwater composition

- Mechanical/geological predictability of the repository formation such that the integrity of the rock structure would not be impaired

- Absence of resources (mineral, water, oil, etc) – or other uses of the host rock

Regarding consideration of geoscientific arguments for safety:

- The most important argument is to present a clear understanding of past geological evolution at the particular site, consistent with the global understanding of geological evolution. Efforts should be made to achieve a broad consensus on this from many independent experts.

- The supporting arguments are seldom based on a single piece of evidence. It is the chain of arguments rather than individual arguments that is important.

- A primary interest is in "reasonable" predictability of the geological system. It is recognized that most geological systems evolve with time, but all details of this are not needed for demonstrating safety. However, there is a need to find well-reasoned bounds for the future evolution.

- Generally, the same type of arguments can be applied for different rock types. The strength of arguments and the time scale of validity, however, vary between host rocks and types. The arguments work better in "simple" systems.

- Sharing experiences between different programs is crucial in assessing strengths and weaknesses in "own" arguments

The confidence with which groundwater flow models can be used is, in part, dependent on the process adopted to develop those models from site-specific data. A scientific programme supporting successive stages in the siting of a disposal facility will evolve as more information becomes available and understanding is refined. It is therefore important that there is demonstrable integration between the data on which understanding is founded, the models that represent that understanding, and the experts involved in both. It is also important that the level of confidence in the models is clearly established.

The development of a conceptual model of the system or subsystem is key to the integration of site characterisation information into a performance assessment. A conceptual model should capture the behaviour of the system and provide the link

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between the underlying data and the numerical models that are used to assess the performance of various components of a repository system. It must be based on, and consistent with, the underlying data, and is progressively refined as more data become available. Conceptual models define key aspects of the numerical groundwater flow models (e.g. the geometry of the system, boundary conditions and time dependency) and also provide the context within which to derive effective parameters to input into these numerical models.

9. *What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.*

Performance assessment calculations should be carried out under an appropriate Quality Assurance regime (such as ISO 9001). It is important that all the data used in a performance assessment are wholly traceable and a source reference available. Likewise, all assumptions should be well documented and any potential biases acknowledged.

As well as relying on QA procedures to give confidence in the results, there is also value in demonstrating an understanding of the system at several levels of complexity, so that the results of complex computer calculations can be supported by simpler models. For example, in the Nirex 95 and Nirex 97 assessments, a simple analytic model of the safety functions of the multiple barrier system was shown to give a good approximation to the results of the more complex modelling for the groundwater pathway. Confidence can be provided in the results of the complex numerical models by showing that similar results may be obtained on the basis of simple models whose basis may be more easily explained and that can be shown to capture the essential features of the system.

10. *What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?*

At the current, generic, stage of the Nirex programme, the arguments that demonstrate that the system can be implemented with existing technology are presented in the 'Viability report' – which is a statement about why Nirex believes its concept is viable [3]. This report identifies the following outstanding uncertainties:

- C-14 has been identified as a key issue in the PGRC. Calculations have been carried out to scope the potential impact of C-14 for two alternative scenarios. In the first of these it is assumed that C-14 all dissolves in groundwater and is released to the biosphere in solution; in this case the calculated risk is well below the regulatory target. The second scenario assumes that carbon-14 is released as gas and all methane generated is

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released directly to the biosphere as gas, taking no account of any delay in the geosphere. In this case, the calculated risk is significantly over the regulatory target. In practice, some of the gas could dissolve in groundwater and the migration of gas in the geosphere would depend on the site geology. In many geological settings, some form of gas retardation may be expected.

- Nirex has an ongoing programme of research on C-14, which is improving our understanding of these issues. Further work is still required, which includes: work to assess the extent to which gas would dissolve in groundwater; work to assess the extent to which different geological environments have the potential to retard gas migration; and work to reduce uncertainties in the rates and quantities of gaseous C-14 generated.

- Non-aqueous phase liquids (NAPLs) are challenging because they can have a greater capacity for uptake of some radionuclides and may migrate more rapidly through the geosphere than groundwater. NAPLs would only leave a repository vault if there was sufficient pooled in the vault to overcome the forces that prevent such materials entering narrow fractures in the host rock.

11. How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.

Once the uncertainties have been quantified, by carrying out scoping calculations either with a probabilistic system model or with deterministic analyses, it is possible to ascertain to which of the uncertainties the performance of the concept is most sensitive, which then can inform

- future research needs – research can be target into trying to reduce the uncertainties that really matter. These research needs, if significant (i.e. costly or time-consuming), may affect the future programme.

- design optimisation – the design of the facility could be modified such that key uncertainties are reduced or engineered out.

12. What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.

As noted above, the regulatory guidance in the UK leads the developer to a probabilistic approach, so such an approach is of most value in communicating the uncertainties to the regulators.

Communication of the uncertainties to non-technical stakeholders is more of a

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challenge. Many researchers have discussed how risk and uncertainty is perceived by non-experts; how the way risk and uncertainty is presented and reported in the media can affect people's perception of it; and how the context in which a risk arises and previous experiences and events can also affect people's perception of the risk.

Scientific uncertainty can undermine public confidence in environmental and technological projects. However, one of the ways that scientists can undermine confidence in their work is by maintaining an exaggerated sense of certainty. Therefore, it is important to be open and honest about uncertainty, and to explain how it is managed and why it is still possible to have confidence in the assessments and the proposed facility.

Explicitly stating the uncertainties associated with assessments will enable stakeholders to develop more informed responses to the situation. It will also help them to engage in the debate and feed back important information about their issues of concern. This could influence the scenarios that are assessed or enable measures to be put in place to lessen the socio-economic impacts of any uncertainties or risks.

13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

Nirex believes that the technical challenges of an appropriate treatment of uncertainty are well understood. The main gaps in terms of the treatment of uncertainty relate to the way in which it is communicated and/or perceived. These are particularly important issues because no matter how much effort is put into a consistent and defensible treatment of uncertainty in a performance assessment, if we are not able to communicate it to stakeholders in such a way that they engage with it, then it is only of limited value. Expert judgement and data elicitation are particular areas in which some stakeholders do not necessarily understand or buy in to our approach.

14. Any other comments?

None.

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15. What are the key references that support your response?

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

2. Nirex, *Generic Post-closure Performance Assessment*, Nirex Report N/80, 2003.

3. Nirex, *The viability of a phased geological repository concept for the long-term management of the UK's radioactive waste*, Nirex Report 122, November 2005.

A15 United States - SNL-WIPP

PAMINA RTDC1 Work Package 1.2: Questionnaire for RTDC1 Participants	
Organisation(s):	Sandia National Laboratories
Responsible Person(s):	Eric Vugrin, Tom Kirchner, Ross Kirkes
Date:	December 18, 2006

1. What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?

The Waste Isolation Pilot Plant (WIPP) is operational. It was first certified on May 18, 1998, and the first waste shipment was received March 26, 1999.

2. What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?

The WIPP-specific Certification Criteria of 40 Code of Federal Regulations (CFR) 194 require that a probabilistic risk assessment be performed and dictates how the "Performance Assessment" (PA) must be conducted. These criteria also detail how uncertainty must be treated.

The following requirements pertain to system parameters:

- Probability distributions for uncertain disposal system parameters must be developed.
- The entire range of the probability distributions must be sampled.
- It is assumed that future drilling practices and technology will remain consistent with current practices.

With regard to repository performance, the following principal regulations exist:

- Features, Events, and Processes (FEPs) that have less than a 1 in 10,000 chance of occurring during 10,000 years do not need to be considered in performance assessment. Probabilities this small would tend to be limited to phenomena such as the appearance of new volcanoes outside of known areas of volcanic activity, and the EPA saw no benefit to public health or the environment from trying to regulate the consequences of such highly unlikely events.
- The results of the performance assessments must be assembled into complementary, cumulative distribution functions (CCDFs) that represent the probability of exceeding various levels of cumulative release.
- The number of CCDFs generated must be large enough such that the

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maximum CCDF generated exceeds the 99th percentile of the population of CCDFs with at least 0.95 probability.

- It must be demonstrated that there is at least 95 % level of confidence that the mean CCDF meets containment requirements.

The containment requirements of 40 CFR 191.13 specify a 10,000 year performance period. A period of 10,000 years was considered long enough to distinguish geologic repositories with relatively good capabilities to isolate wastes from those with relatively poor capabilities. This period was considered short enough so that major geologic changes would be unlikely and repository performance might be reasonably projected.

In addition to complying with radionuclide release limits, the WIPP must comply with individual and groundwater release protection standards. To demonstrate compliance with these standards, PA results are used, along with other tools, in the compliance assessment, and the uncertainty is accounted for in a manner similar to that in the PA.

For a complete listing of regulations that pertain to the WIPP, go to the website http://www.access.gpo.gov/nara/cfr/waisidx_04/40cfr194_04.html. Sections 194.25, 194.26, 194.28, and 194.32 all pertain to how uncertainty must be handled in performance assessment.

3. How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.

The performance calculations for WIPP 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 model (CCDFGF) to estimate potential releases. All 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 three hundred sets of values (sampled using Latin hypercube sampling) for the parameters and running the models for each set. A fixed set of scenarios is applied to the process level models. These scenarios represent the repository in an undisturbed state and in various states following drilling intrusions into the repository. CCDFGF simulates releases from the repository over a 10,000-year period following closure of the facility. The timing and location of intrusion events, the type of waste encountered by drilling events, penetration of brine pockets and the way in which the boreholes are plugged are all treated as stochastic events in CCDFGF. CCDFGF generates 10,000 possible futures for each of the 300 sets of results from the process-level models. Uncertainties regarding the scenarios that are modelled or associated with the structure and assumptions of the process level models are not considered in the PA calculations.

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We assume that there are no uncertainties associated with the models (conceptual, numerical, etc.). However, we do address uncertainty modelling assumptions. Examples include: instantaneous equilibrium and batch reactor chemical environment for chemistry models, brines have access to all actinides, etc. Thus, some model uncertainties are accounted for through assumptions and modeling approaches. These assumptions are generally conservative in nature.

4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

The epistemic uncertainties associated with parameters are defined by distributions that are assigned to the parameters. These are propagated through the deterministic models by sampling the distributions with a Latin hypercube method to generate 300 sets of parameters, and then running the models for each of these sets. Aleatory uncertainty associated with potential drilling intrusions into the repository are modelled as stochastic events. Ten thousand possible futures are generated for each of the 300 sets of parameters and a single CCDF is generated from the 10,000 futures. Thus, the model results consist of 300 CCDF curves. Variability across the 300 curves is interpreted as uncertainty in the probability of a release of a given magnitude rather than the uncertainty in the magnitude of release at a given probability. The wider scope of safety issues would probably consider risks to the workers involved in the construction, maintenance and use of the facility, risks to those handling the waste, transportation risks, etc. These risks are not considered in the WIPP PA but are addressed separately.

5. How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.

A screening process was used to identify the potentially significant FEPs that could have an impact on the performance of the repository. These were then either explicitly represented in the process level models or implicitly accounted (e.g., via modelling assumption) for in one or more of the scenarios that the models simulated. All uncertainty in the deterministic process-level models was assumed to be due to uncertainty in their parameters, and that uncertainty was either quantified from data, when available, or by using subjective methodologies. The level of information on which to base the assignment of the distributions of possible values varied greatly among the parameters. The level of knowledge was 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

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assumptions have been made in these instances.

6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?*

The regulations under which WIPP operated require a probabilistic risk assessment be performed. In addition, the regulations specify that certain kinds of releases, e.g. those associated with groundwater, always be considered independent of the potential magnitude of those releases. The releases associated with groundwater require using relatively complex models. Some simplification was required, however, due to computational limitations. Therefore, the calculation of releases relies on the use of response surfaces generated from running a limited set of scenarios across 300 sets of parameters.

The WIPP PA, like many risk assessments, is a mixture of both conservative and realistic approaches. The process-level models are compromises between striving for realism and the constraints imposed by limitations on computer resources and data availability. In the case of the hydrologic models, for example, these compromises influence the scale and resolution of the grid being simulated. The selection of parameters is thus made with the knowledge of limitations imposed by scale and resolution of the models, which can lead to the assignment of "appropriate" values rather than simply "realistic" values. In some cases the regulator for the site has dictated the range of values to be covered by distributions, and these invariably tend to be conservative in the sense of maximizing releases. In other cases the modellers may choose to use conservative values, particularly when the consequence of doing so is small compared to the effort it would take to provide, and have approved by the regulator, more realistic values.

7. *How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.*

The evaluation of uncertainty in the model projections is used to support the conclusion that the facility will meet compliance requirements. Uncertainty in the results is assumed to be due to uncertainty about the parameters used in the process-level models. This uncertainty is propagated using Monte Carlo methods.

Thus far, sensitivity analyses have been conducted using regression analysis on the inputs and the results generated by the uncertainty analysis. Although this approach limits the kinds of analyses that can be performed, the computational requirements of the WIPP PA system prevent the consideration of the specialized and more extensive sampling designs required by some alternative methods. In addition, the use of regression techniques has been adequate in terms of identifying the dominant

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parameters contributing to uncertainty.

8. *What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.*

The models and their parameters have been subjected to external peer review. The distributions assigned to the model parameters have been scrutinized and approved by the regulators of the facility. Public confidence in the long-term safety of the repository is derived through trust in the regulators for the facility, the US Environmental Protection Agency (EPA) and the New Mexico Environment Department (NMED). Confidence by the regulators is gained by providing full access to the data, codes and methods used to perform the PA; by estimating uncertainties on the projections using establish methods; by performing tests to verify and validate the codes; by maintaining an approved Quality Assurance (QA) program to enforce the utilization of approved codes and data and to provide documentation that describes the various analyses conducted in the PA; and by using additional analyses beyond the baseline PA to examine the impact of assumptions, requirements, parameters, and methods used in the PA.

Furthermore, the project includes public stakeholder input through a variety of different opportunities. These opportunities include interactions through technical exchanges with the regulators and DOE, formal public comment periods, a WIPP hot line, and independent technical oversight.

Finally, the DOE must apply for recertification every five years. In the original certification application and subsequent recertification applications, the DOE must document how uncertainty and other issues are handled. The WIPP is a licensed and operational facility because the regulator reviewed the original certification application and subsequent recertification application and approved both.

9. *What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.*

A parametric uncertainty analysis, such as that done for WIPP PA, can only provide an estimate of the quality of the assessment within the bounds of the modelling framework, assumptions and the uncertainties assigned to the parameters. In other words, the uncertainty analysis expresses the range of possible releases or risks given that the conceptual models capture all the important process and events affecting the future of the repository, that the conceptual model has been properly implemented in code, that the numerical methods applied to solve the computer models are implemented properly and of adequate precision, that the assumptions made in developing the models are reasonable, that the parameters used are appropriate for the scale of the implementation, that the code and its inputs are protected from unauthorized changes, etc. Thus, by itself it cannot provide an estimate of the

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validity of those calculations. Confidence in the validity of the calculations must be established through a variety of other means. Lack of such confidence can result in the perception among reviewers, regulators and the general public that the uncertainties in the predictions far exceed those reported. Thus efforts to demonstrate the overall credibility of the approach used in the assessment are likely to be important. These efforts include such things as configuration control for all related computer files, documentation of changes and their impacts, verification and validation of the models, use of formalized methods for assessing uncertainties subjectively, peer review down to the level of the code, etc. Putting these additional activities under QA can help to confirm that the approved methodologies are being used. However, care must also be taken to help ensure that the requirements and delays imposed by QA do not detract from the quality of the assessment.

For the WIPP project, the regulator recognized the overall uncertainty of the performance predictions. EPA states in 40 CFR 191.13(b), "Performance assessments need not provide complete assurance that the requirements of §191.13(a) [the release limits] will be met. Because of the long time period involved and the nature of the events and processes of interest, there will inevitably be substantial uncertainties in projecting disposal system performance. Proof of the future performance of a disposal system is not to be had in the ordinary sense of the word in situations that deal with much shorter timeframes. Instead, what is required is a reasonable expectation, on the basis of the record before the implementing agency, that compliance with §191.13(a) will be achieved." It is important for all participants of the project to recognize that there will always be uncertainties relating to long-term predictions and that the best practice to account for these uncertainties uses both quantitative and qualitative methods that are defensible, justified, reproducible and reasonable.

10. What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?

The key long-term performance measure for the WIPP is the total cumulative release of radioactivity to the environment. Solid waste material removed from the repository by the drill bit and shearing forces of the drilling fluids during a drilling intrusion account for an overwhelming majority of the total releases. These solid waste materials are termed "cuttings and cavings." Uncertainty in total normalized releases is largely due to uncertainty in waste shear strength. In fact, shear strength accounts for more than 88% of the variability in total releases. The uncertainty in the volumes of cuttings and cavings is primarily controlled by shear strength. The second most important variable is a "solubility multiplier" that represents uncertainty in solubilities for all actinides in the +III oxidation state. This variable accounts for approximately 2% of the variability in total releases. The drill string angular velocity, also used in computing cuttings and cavings, contributes to about 1% of the

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variability of total releases. Each of the remaining parameters explain less than 1% of the variability in the total releases.

PA models are modified to incorporate changes to repository design, contents, and uses. The simplest way to receive approval from the regulator for the model changes is to implement them in a "bounding" manner. However, if this is the only approach taken to introduce change, the system that is modeled and the performance predicted will not resemble the actual performance of the repository, and, it may appear that a change will have a large, adverse impact on the performance of the repository when in fact it may not. Care must be taken to implement future changes with the best science and engineering information available.

11. *How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.*

During late site characterization and early PA development, the project performed a systems prioritization where PA tools were used to determine the sensitivity of parameters under investigation to PA outputs. This information was used to prioritize experimental and other site characterization work that was ongoing with the intent of developing or justifying PA parameters. Highly sensitive elements were given priority while less sensitive elements were reduced or eliminated. This prioritization resulted in better management of resources and expedited the final PA and compliance certification application.

After the site was operational, sensitivity assessments, operational efficiency changes and other drivers led the project to investigate many PA related elements such as ground water level anomalies in the WIPP vicinity and refinements in models and computer codes to increase efficiencies and assess changes to the repository designs. This type of information is necessary for periodic compliance recertifications and change requests.

12. *What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.*

The focus of WIPP PA has always been on the presentation of the CCDFs for the releases, primarily because those are the key to showing compliance with the governing regulations. In the graph below the total normalized releases computed for two assessments are compared and shown relative to the release limits set by regulations.

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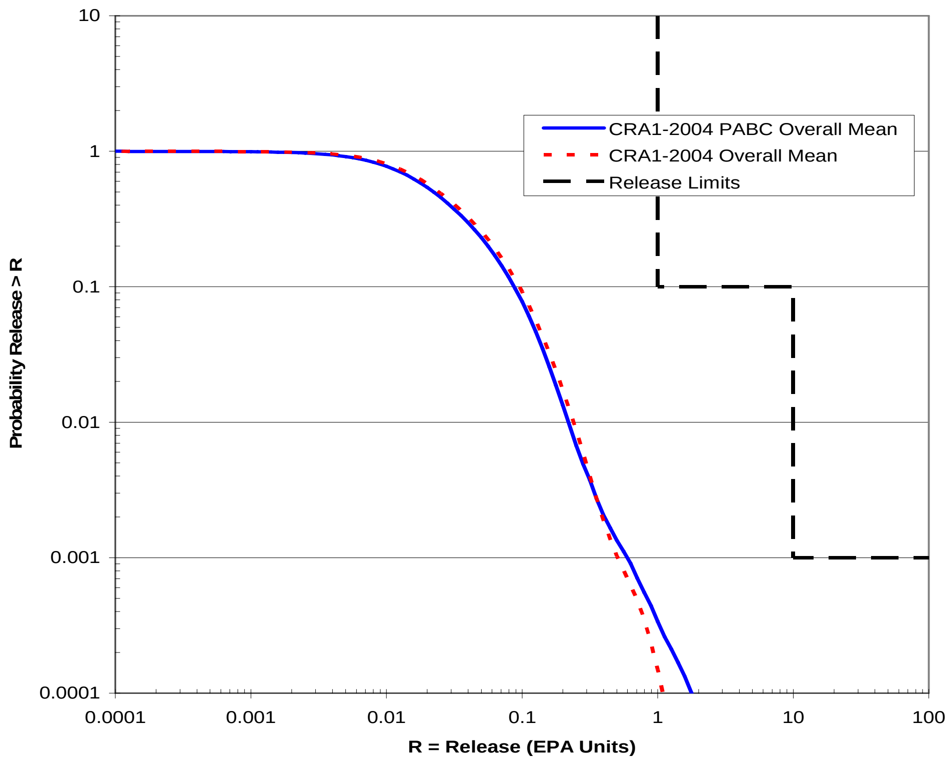

13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

14. Any other comments?

Sandia is a multi program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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15. What are the key references that support your response?

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A16 United States – USDOE-Yucca Mountain Project

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1. What stage is the radioactive waste disposal programme at in development (concept assessment, general siting, detailed site characterisation, final licensing to start construction / operation, operations)?

The Yucca Mountain Project is to submit a license application in 2008 to the U.S. Nuclear Regulatory Commission (NRC), to obtain a construction authorization.

2. What are the principal regulatory compliance requirements for long-term safety of the waste disposal system, particularly those that pertain to treatment of uncertainty?

The U.S. Environmental Protection Agency (EPA) and the NRC are currently in the process of developing the standards that will apply to the disposal of high-level radioactive wastes in the potential repository at Yucca Mountain (proposed 10 CFR Part 63 [64 FR 8640]). 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

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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)

The regulatory guidelines also require a demonstration of reasonable expectation in the compliance calculations vis-à-vis the following acceptance criteria:

- Does not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence;
- Focuses performance assessments and analyses on the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values

The EPA has recently proposed public health and safety standards in proposed 40 CFR Part 197 (64 FR 46976), with which the potential repository at Yucca Mountain must comply. The EPA has also specified the application of a probabilistic framework where uncertainties associated with scenarios, models, and parameters are explicitly incorporated into the performance assessments for demonstration of compliance. The regulation specified by the NRC in proposed 10 CFR Part 63 (64 FR 8640) is intended to implement EPA's standards and be consistent with the EPA requirements.

3. How have the main types of uncertainties been classified for consideration (e.g., scenario, model, parameter, others)? Please provide examples.

The assessment of long-term performance for the potential high-level radioactive waste repository at Yucca Mountain is a complex endeavor. It requires modeling various coupled hydrologic, geochemical, thermal, and/or mechanical processes taking place within the engineered and natural barriers over extended periods of time. In addition, the future evolution of the geologic and environmental conditions surrounding the disposal facility must also be considered, albeit in a somewhat stylized manner. Such integrated assessments of the future behavior of the disposal system via a total system performance assessment (TSPA) model are often

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complicated by uncertainties which arise due to incomplete understanding, limited information, and/or paucity of data. These uncertainties may be further categorized as follows:

- Scenario uncertainty
- Model uncertainty
- Parameter uncertainty and/or variability.

Scenario uncertainty stems from the fact that future evolution of geologic and environmental conditions surrounding the disposal facility, over tens of thousands of years, is inherently unpredictable. Scenarios of plausible future states of the system, and their likelihood of occurrence, must therefore be inferred from direct and/or indirect field evidence and incorporated into the performance assessment analyses. An example of an uncertain scenario is volcanic activity resulting in upward magma flow to the repository horizon and damage to waste containers.

Model uncertainty includes uncertainty in conceptual models and assumptions, uncertainty in mathematical descriptions of these conceptual models, as well as uncertainty in numerical implementations in computer codes. Because of incomplete understanding and characterization of FEPs, multiple plausible alternative conceptual models may be considered equally likely or defensible. This is often the major source of model uncertainty. Translation of a conceptual model into a mathematical model also results in uncertainties because of simplifications and approximations commonly employed to make the problem tractable. An example of model uncertainty is the representation of unsaturated flow at Yucca Mountain using the active fracture model. Conceptually, the problem involves simplifying the characterization of water flow through a complex fractured rock mass using a simple dual-continuum fracture-matrix model. Additional uncertainty is introduced through the assumptions inherent in mathematical representations of fracture-matrix interaction and numerical solution of the governing equations, and calibration to field conditions using only a limited amount of data.

Parameter uncertainty may be categorized either as aleatory uncertainty, or as epistemic uncertainty. Aleatory uncertainty arises due to the inherent unpredictable nature of future events (as random processes/chance occurrences) and cannot be reduced by further collection of information after the repository system is designed. The time of an igneous or seismic event, or the number of waste packages destroyed in an igneous event, are examples of aleatory variables in the TSPA analyses. Aleatory uncertainty is also referred to as stochastic uncertainty, irreducible

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uncertainty or natural randomness (variability). Epistemic uncertainty arises due to lack of knowledge about the true, non-random, values of parameters and can be reduced by additional information. Model parameters such as spatially-averaged values of hydraulic conductivity are examples of epistemic variables in the TSPA analyses. Epistemic uncertainty is also referred to as subjective uncertainty or reducible uncertainty.

The presence of uncertainty in the inputs of the TSPA model (i.e., scenarios, mathematical and conceptual models, and parameters) results in the output of the model being uncertain as well. A probabilistic framework has been adopted in the Yucca Mountain project for translating uncertainties in model inputs to corresponding uncertainties in model predictions. This approach is also consistent with the regulatory standards proposed by the NRC and the EPA.

4. How have the different types of uncertainty been dealt with in the quantitative PA, and how have they been dealt with as part of the wider safety case? Please provide examples of each.

Question 6 answers the PA part fully. The safety case part is currently being planned, but not yet done. Perhaps uncertainties will be discussed in the safety case in a less technical manner as was previously done in sections 5.2.4.3.3 through 5.2.4.3.6 of the Yucca Mountain Final Environmental Impact Statement, which can be read at http://www.ocrwm.doe.gov/documents/feis_a/vol_1/eis05_bm.pdf. In these four sections there is a general discussion of uncertainties, specific discussions disclosing quantified and unquantified uncertainties, and a discussion of the main results of uncertainty and sensitivity analyses.

5. How much knowledge is there to define the main uncertainties, and how does the level of knowledge dictate the treatment of the uncertainties? Please provide examples.

A systematic methodology is employed where the level of knowledge dictates how uncertainty is characterized. If enough data are available from (a) field, laboratory and/or numerical experiments, (b) historical sources or (c) analog sites, then probability distributions are fitted to the data. Maximum entropy approaches are used to derive distributions when only a limited amount of information is available about the variable of interest. Formal expert elicitation protocols are applied to create subjective distributions when no site-specific information is available. Finally, Bayesian updating is used to combine old information (e.g., expert elicitation from a previous TSPA) with new measurements (e.g., results of recent field experiments). Documents have been written that provide guidance on how

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each of these methods can be applied.

6. *What approach to system PA is preferred / appropriate and why (e.g., conservative versus realistic; deterministic versus probabilistic versus deterministic complemented by probabilistic; simplified versus complex modelling; use of "fuzzy mathematics"; others)?*

The approach is to strive for a realistic (i.e., unbiased) characterization of uncertainty where possible and to adopt a conservative approach where realism is difficult to defend.

The regulatory requirements prescribe a probabilistic framework for incorporating the effects of uncertainties in scenarios, conceptual models, and/or parameters on evaluation of long-term system behavior. It has been extensively used in probabilistic risk analyses for evaluating the safety of nuclear reactors and power plants. Several probabilistic performance assessments have also been carried out within the U.S. radioactive waste disposal program. These include a series of performance assessment studies for the disposal of transuranic waste at the Waste Isolation Pilot Plant, as well as a series of calculations performed for the disposal of high-level radioactive waste at Yucca Mountain by the DOE and the NRC.

Monte Carlo simulation, the most commonly employed technique for implementing the probabilistic framework in engineering and scientific analyses, is a numerical method for solving problems by random sampling. This method allows a full mapping of the uncertainty in model parameters (inputs) and future system states (scenarios), expressed as probability distributions, into the corresponding uncertainty in model predictions (output), which is also expressed in terms of a probability distribution. Uncertainty in the model outcome is quantified via multiple model calculations using parameter values and future states drawn randomly from prescribed probability distributions. Monte Carlo simulation is also known as the method of statistical trials because it uses multiple realizations of the inputs to compute a probabilistic outcome.

The probabilistic modeling approach is computationally burdensome because it requires several hundred model calculations for each scenario of interest. However, it also provides important information not available from a deterministic "best-guess" or "worst-case" calculation. The benefits of probabilistic modeling include (1) obtaining the full range of possible outcomes (and the likelihood of each outcome) to quantify predictive uncertainty and (2) analyzing the relationship between the uncertain inputs and the uncertain outputs to provide insight into the

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most important parameters.

A Monte Carlo analysis of the TSPA model involves the following four steps:

1. Select imprecisely known model input parameters to be sampled
2. Construct probability distribution functions for each of these parameters
3. Generate a sample set by selecting a parameter value from each distribution
4. Calculate the model outcome for each sample set and aggregate results for all samples.

These steps are briefly described below.

Selecting Imprecisely Known Model Input Parameters To Be Sampled – The TSPA model consists of approximately 2,000 parameters, many of which are uncertain and/or variable. A determination as to which of these have a significant range of uncertainty or variability, affect the response of the performance measure(s) of interest, and thus need to be statistically sampled during model calculations, is made during the development of individual process models and/or abstractions thereof.

Constructing Probability Distribution Functions for Each Parameter – The probabilistic framework employed in Monte Carlo simulations requires that the uncertainty in model inputs be quantified using probability distributions. A variety of methods is used in the TSPA process for developing proper input distributions:

- fitting parametric distributions to measured, historical or analog data,
- using maximum entropy approaches to assign probability distributions based on minimal information about range/shape, and
- eliciting subjective judgment of domain experts using formal protocols and aggregating them to create composite distributions
- using Bayesian updating as an objective framework for combining old information (e.g., expert elicitation) with new data (e.g., field measurements)

Generating a Sample Set by Selecting a Parameter Value from Each Distribution – The next step in the Monte Carlo process requires generating a number of equally likely input data sets, which consist of parameter values randomly sampled from the prescribed range and distributions. An improved form of random

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sampling is the Latin hypercube sampling procedure, where the range of each parameter is divided into several intervals of equal probability and a value is selected at random from each interval. Latin hypercube sampling, which is employed in TSPA, helps achieve a more uniform coverage of the uncertain parameter range as compared to purely random sampling. The issue of interdependence or statistical correlation between parameters is also important from the perspective of maintaining the necessary dependence between random variable pairs. The sampling algorithm used in TSPA ensures that any desired correlation between input parameters is retained.

Calculating Outcomes for the Sample Set and Aggregating Results for All Samples – In this step of the Monte Carlo methodology, the model describing the behavior of the system for the scenario of interest is evaluated for each of the randomly generated parameter sets. This is a simple operation consisting of multiple model calls, where the outcome (i.e., annual dose as a function of time) is computed for each sampled parameter set. One key consideration in this step is ensuring that enough simulations have been performed to obtain a stable solution via statistical tests of convergence, as well as parametric and non-parametric estimates of the reliability in statistical measures of model output. Once all of the required model runs have been completed, the overall uncertainty in the predicted outcome can be characterized by (1) summary statistics such as the mean and median and (2) the cumulative probability distribution.

Recall that the uncertainty in system performance (total system or subsystem), caused by the aleatory variables cannot be reduced, and the uncertainty caused by epistemic variables can be reduced by collection of additional information. Thus, interest centers on quantifying the uncertainty that can be reduced (reducible uncertainty), and further, to identify the important drivers of this reducible uncertainty, by the methods of sensitivity (uncertainty importance) analyses. This requires computing the reducible uncertainty and, therefore, maintaining a distinct demarcation between the aleatory and epistemic variables whenever that is practicable. The corresponding computational strategy involves selecting a sample of the all the epistemic variables, and, calculating for this sample, the expected performance over the set of aleatory variable(s). This procedure is repeated for other samples of epistemic variables, so that one obtains, the expected performance of the system (the expectation being only over the aleatory uncertainties such as timing of igneous event) for a set of samples of epistemic variables.

With respect to the nature of models used (i.e., simple versus complex), the GOLDSIM used by DOE for TSPA calculations allows models of any level of

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complexity to be utilized. However, from a computational tractability perspective, primarily abstracted models are used in the TSPA process. For each of the sub-components in the total system model, an evaluation is carried out to determine the best form for the abstraction. In some cases, the results of detailed process models are captured as multi-dimensional response surfaces (e.g., in-package chemistry). In other cases, results of probabilistic process models are captured through a few discrete cases that are weighted appropriately to preserve the first few moments of the relevant performance measure (e.g., multi-scale thermal hydrology). Yet another example of model simplification involves developing transfer functions based on linear system theory to reduce 3-D models to 1-D models (e.g., using breakthrough curves and convolution theory to model saturated zone behavior).

7. How does the PA conduct and differentiate between sensitivity analysis and uncertainty analysis? Please provide examples.

Uncertainty analysis refers to the translation of uncertainties in model inputs into the corresponding uncertainties in model outputs. As noted earlier, uncertainty analysis is carried out using Monte Carlo simulation. Results are presented in terms of: (a) probabilistic time history of subsystem (e.g., mass release) and total system (e.g., annual dose), (b) corresponding statistics (e.g., mean, median, 5^{th} and 95^{th} percentiles of time histories), (c) dominant radionuclides contributing to mean dose.

Sensitivity analysis involves examining the sensitivity of the TSPA model results (and their uncertainties) to the uncertainties and assumptions in model inputs. This is accomplished using (a) regression analysis to determine the most important contributors to the spread in probabilistic model results, (b) classification tree analysis to identify those variables controlling extreme outcomes in the full suite of probabilistic results, and (c) entropy analysis to quantify the strength of input-output association for non-monotonic patterns. Note that these are global sensitivity analysis techniques that rank the uncertainty importance of various uncertain inputs by taking into account both the degree of uncertainty in the input and input-output sensitivity. This is different from the standard one-parameter-at-a-time local sensitivity analysis which captures only the input-output sensitivity at a reference point.

The TSPA sensitivity analyses are carried out using results from the probabilistic calculations at a fixed point in time, with the sampled inputs corresponding to each of the realizations being treated as independent variables and the computed outputs being treated as dependent variables. Note that the outputs can either be total system-level performance measures, such as annual dose rate to a receptor, or they

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can be subsystem-level performance measures, such as cumulative radionuclide mass flux at the water table.

Regression Analysis – In performance assessment studies, multiple linear regression modeling is commonly used to identify input variables that contribute the most to the calculated uncertainty (variance) in the performance measure. The primary technique for regression modeling is stepwise linear regression using rank transformations of the input and output values. The indicators for determining the relative importance of the input variables are the partial rank correlation coefficient and the standardized regression coefficient. Both of these indicators are calculated during stepwise regression modeling. The partial rank correlation coefficient for a particular input variable measures the correlation between the output and the selected input variable, after the linear influences of the other variables in regression have been eliminated. The standardized regression coefficient is related to the fraction of the total explained variance in the regression model that can be attributed to the variable of interest.

Classification Trees Analysis – Linear regression is useful for analyzing entire spectra of output data. However, analyzing small categories of output data may require a more specialized approach. Classification tree analysis is a categorical method for determining what variables or interactions of variables drive output into particular categories. Those realizations that yield the highest and lowest outcomes are grouped into high and low categories. Classification tree analysis will then provide insight into what variable or variables are most important in determining whether outputs fall in one or the other category. This leads to the extraction of useful decision rules such as "IF $x1<a$ AND $x2>b$ THEN dose > 90th percentile".

Mutual Information (Entropy) Analysis – This approach is particularly useful for detecting non-monotonic input-output relationships. It involves constructing a contingency table that has entries of nonnegative integers giving the number of observed events for each combination of input variable (x) state and output variable (y) state. The mutual entropy (information) between x and y is a measure of the reduction in uncertainty of y due to knowledge of x (or vice versa). It can be computed by counting the number of occurrences of various states of x alone, y alone, and xy together. The strength of association in the contingency table is quantified using the R-statistic, which is a generalization of the coefficient of linear (monotonic) correlation.

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8. What supporting arguments are available / relevant to address uncertainties and provide confidence in long-term safety? Please provide examples.	
Confidence is enhanced by demonstrating robust multiple barriers, using natural analogs where appropriate, showing that a detailed characterization of the repository has been performed at the component and system levels, comparing intermediate results from the system-level model with process model results, comparing with other comparable system-level analyses where appropriate, peer reviews, and also institutional actions including performance confirmation monitoring, site controls, QA, and assuring a safety-conscious work environment.	
9. What measures other than numerical analysis can be utilised to manage the uncertainties (e.g., methodological, QA, etc.)? Please provide examples.	
Showing that a reasonable estimate has been made insofar as data has allowed, and where there was a sparsity of data, conservative estimates have been made to avoid underestimating risk.	
10. What are the main uncertainties with regard to key performance measures / objectives and the purpose of the safety case at its current status? What is the likelihood that the uncertainties may jeopardise the project at a later stage?	
In the DOE's Site Recommendation was accompanied by a "Yucca Mountain Science and Engineering Report (2002, sections 1.4.3; 4.1.1 and 4.4.5), uncertainties and their importance are discussed. But these analyses are now out of date and new analyses to support licensing are in progress. We do not believe that the remaining uncertainties preclude submittal of a license application. Link to internet for the cited document: http://www.ocrwm.doe.gov/documents/ser_b/index.htm	
11. How are the uncertainty analysis results and other measures of uncertainty management used to derive conclusions and focus future work (e.g., programme decisions, R&D priorities, design requirements or modifications, license submissions)? Please provide examples.	
Long-term performance assessment of geologic disposal systems are significantly impacted by uncertainties arising from ignorance or imperfect knowledge about future events, processes and/or parameters as well as differences attributable to geologic heterogeneity. In the Yucca Mountain project, a systematic and comprehensive methodology has been developed for dealing with these uncertainties in a manner consistent with regulatory requirements. To that end, the combination	

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of uncertainty and sensitivity analyses techniques described above facilitates the quantification of uncertainty bounds on predicted radiological and non-radiological consequences, as well as the identification of key processes and parameters governing disposal system response for the proposed Yucca Mountain repository.

12. What works best in communicating the different types of uncertainty to regulators and to other stakeholders (e.g., alternative approaches to presentation of results, etc.)? Please provide examples.

Regulatory requirements include consideration of uncertainty, and the mean is the primary regulatory metric. Given regulatory expectations for evaluations of stability of the mean and uncertainty in the mean, we generally display the mean with the full distribution of results from which it is derived, along with selected quantiles such as the 5^{th} and 95^{th} percentiles. This seems to satisfy almost all non-technical audiences.

13. With reference to the responses to previous questions, what are the gaps in understanding of how uncertainty should be classified, managed, analysed, supported with qualitative argument, presented, used to derive conclusions about future work, communicated, etc. that could usefully be considered as part of RTDC2, and why are these gaps important.

In the US regulatory framework the classification and management of uncertainty is addressed jointly by both the regulator and the implementer. The DOE believes the approach it has taken is adequate and appropriate to support the decision-making process associated with DOE’s submittal of the license application.

14. Any other comments?

No.

15. What are the key references that support your response?

The CFRs mentioned above are part of the Code of Federal Regulations available on the internet at http://www.gpoaccess.gov/cfr/index.html. A reference was given in parts 4 and 10, above.