EUROPEAN COMMISSION

Community research

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

**(Contract Number: FP6-036404)**

## Scenario Uncertainty

## DELIVERABLE (D-N°: D2.2.C.1)


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Version: Version 1

Date of issue of this report : **20/11/2009**

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 2.

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

Deliverable D2.2.C.1
Version 1 Draft 1

# Scenario Uncertainty

**Report History**

This document has been prepared under the PAMINA Project for the European Commission by Galson Sciences Limited (**GSL**), in partial fulfilment of Contract FP6–036404. GSL acknowledges cofunding from ONDRAF/NIRAS to write this PAMINA Task Report.

This document is PAMINA Deliverable D2.2.C.1, and it summarises the work described in three PAMINA Milestone Reports: M2.2.C.1, M2.2.C.2, and M2.2.C.3. The organisations that contributed to these reports were: the French Commissariat à l'énergie atomique (**CEA**), **GSL**, the Nuclear Research and consultancy Group **(NRG)** in the Netherlands, the Nuclear Research Institute Řež (**NRI**) in the Czech Republic, and the Technical Research Centre of Finland (**VTT**).

Version 1 of this report is issued for publication and responds to comments on Version 1 Draft 1 (dated 6 November 2009).

| **Scenario Uncertainty** | | | | |
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| Version: | Date: | Principal Author:<br>D.A. Galson | Reviewed by:<br>P.J. Hooker | Approved by:<br>D.A. Galson |
| D2.2.C.1<br>Version 1 | 20 Nov 2009 | Sign<br>……………………<br>Date<br>…………………… | Sign<br>……………………<br>Date<br>…………………… | Sign<br>……………………<br>Date<br>…………………… |

# Executive Summary

The European Commission's PAMINA Project (***P***erformance ***A***ssessment ***M***ethodologies ***in*** ***A***pplication to Guide the Development of the Safety Case) has the aim of improving and developing a common understanding of integrated performance assessment (PA) methodologies for the disposal of spent fuel and other long-lived radioactive wastes in a range of geological environments. The project work is organised within five Research and Technology Development Components (RTDCs). Galson Sciences Limited (**GSL**) is responsible for the co-ordination and integration of RTDC2, which is designed to develop a better understanding of the treatment of uncertainty in PA and safety case development. As part of RTDC2, Task 2.2.C aims to evaluate methods for the treatment of uncertainties associated with scenarios, that is, uncertainty associated with what might happen to a disposal system in the future.

The issues to be considered in determining scenarios for PA can be divided into four questions, all of which give rise to uncertainties:

(a) *What might happen and how might it happen (scenario comprehensiveness)*?

(b) *How likely is it to happen (scenario probability)*?

(c) *What are the consequences of it happening (scenario implementation)*?

(d) *How can stylised scenarios (i.e. future human actions scenarios) be conceptualised?*

Task 2.2.C focuses on three high-level topics to provide some answers to these questions (except question (c), which is usually answered through PA calculations):

| | |
|---|---|
| Topic 1 | Review of scenario development methodologies with respect to treatment of uncertainty and the issue of comprehensiveness – addresses question (a). [Contributor: Commissariat à l'énergie atomique (**CEA**), France.] |
| Topic 2 | Quantifying probabilities for scenarios – addresses question (b). [Contributors: **GSL** (international review), Technical Research Centre of Finland (**VTT**, review of practice in Scandinavia), and Nuclear Research Institute Řež (**NRI**, review of practice in the Czech Republic, review of formal use of expert judgement).] |
| Topic 3 | Trial of formal use of expert judgement for scenario conceptualisation – addresses question (d). [Contributor: Nuclear Research and consultancy Group (**NRG**), Netherlands.] |

The three topics were covered by performing detailed reviews and conducting research by means of case studies selected from the programmes of participating organisations and from wider review. The findings are described in three separate Milestone Reports:

- A. Bassi and N. Devictor. PAMINA WP2.2C: Review of scenario development methodologies, M2.2.C.1, March 2008.

- D.A. Galson, R.D. Wilmot, J.E. Morris, D. Reedha, H. Nordman and A. Vokal. PAMINA WP2.2C Topic 2: Quantifying scenario probability, M2.2.C.2, September 2009.
- J.B. Grupa. PAMINA WP2.2C Topic 3: Trial of formal use of expert judgement for scenario conceptualisation, M2.2.C.3, September 2009.

This Task Report provides guidance for the treatment of uncertainties based on the material developed under Task 2.2.C. Key guidance contained within the three Milestone Reports developed under Task 2.2.C is summarised below.

**Scenario Development**

- Considerable uncertainties are associated with the question of what might happen to a geological disposal system. To ensure that a PA is comprehensive and robust, the consequence and likelihood of occurrence of alternative futures or scenarios need to be considered.
- A structured and well-documented approach to the identification and screening of features, events and processes (FEPs) has frequently been used to justify the selection of a representative set of scenarios for analysis. Screening criteria, based on the probability of occurrence and/or consequences to the performance of the disposal system, should be used to screen out FEPs that are unlikely to occur or that have relatively minor consequences.
- The screened-in FEPs are used to formulate a *reference* or base-case scenario, including all expected FEPs, their interactions and developments over time, often considered in discrete periods after closure of the disposal facility. The reference scenario describes the normal evolution of the disposal system within the expected range of uncertainty, and is assumed to have a probability of one.
- *Altered evolution scenarios* or alternative scenarios are less likely than the reference scenario, and these are developed on the basis of perturbations of the normal evolution of the disposal system.
- *Bounding* scenarios portray extreme events that are still within the range of realistic possibilities.
- *"What if"* or residual scenarios may be considered highly implausible or even impossible, and are given a nominal probability of zero.
- *Stylised* scenarios are used to treat inadvertent human intrusion events that involve large and irreducible uncertainties.

**Quantifying Scenario Probabilities**

Given the large uncertainties involved, the main consideration in the assignment of probabilities to events, processes and scenarios is credibility. Some considerations that will enhance the credibility of probability estimates include:

- Careful interpretation of data in the geological and/or historical record.

- Careful explanation that most scenario probabilities should be considered as "degrees of belief" rather than relative frequencies. If frequency data are available, the analysis will be conditional on the assumptions regarding the use of such data to make projections into the far future.
- Use of modelling approaches to simplify assessments, and clear representation of the factors that could increase or reduce any estimate of scenario probability.
- Avoidance of probability estimation where insufficient information is available, or where assessment outcomes do not depend on this probability, or where siting has already explicitly considered the issue and there is nothing that can be done to reduce the probability further.
- The use of formal expert judgement techniques where the safety case outcome relies significantly on assessments of scenario probability.

**Formal Use of Expert Judgement**

The elicitation procedure developed for obtaining statistical distributions for quantitative target variables through expert judgement is also useful for qualitative target variables. Agreements between the experts might be used as a way to improve the basis for a given scenario, while differences might be resolved either by widening the uncertainty related to the scenario (to cover different experts' views), or by iterative expert elicitation steps.

It is suggested that the responses of the experts for qualitative target variables are recorded in the relevant FEPs in the FEP database used for scenario development. For future expert judgement studies for scenario development, it is recommended that the procedure states that the responses of the experts will be recorded in the FEP descriptions. When the FEPs are used in scenario development, it can be decided which expert's view is most applicable to the scenario(s) under consideration.

For quantitative target variables, it is recommended that a scheme is developed that ensures that the qualitative arguments of the experts are available when the results are evaluated for use. This may be a better approach than weighting the experts' views using a scheme that may not be appropriate to the situation in which the quantitative results are eventually used.

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# Scenario Uncertainty

# 1 Introduction

## 1.1 Background and Aims

The European Commission's PAMINA Project (***P***erformance ***A***ssessment ***M***ethodologies ***in A***pplication to Guide the Development of the Safety Case) has the aim of improving and developing a common understanding of integrated performance assessment (PA) methodologies for the disposal of spent fuel and other long-lived radioactive wastes in a range of geological environments. The project work is organised within five Research and Technology Development Components (RTDCs).

Galson Sciences Limited (**GSL**) is responsible for the co-ordination and integration of RTDC-2, which is designed to develop a better understanding of the treatment of uncertainty in PA and safety case development. As part of RTDC-2, Task 2.2.C aims to evaluate methods for the treatment of uncertainties associated with scenarios, that is, uncertainty associated with what might happen to a disposal system in the future.

The issues to be considered in determining scenarios for PA can be partitioned into four questions, all of which give rise to uncertainties:

(a) *What might happen and how might it happen (scenario comprehensiveness)*?

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Work under Task 2.2.C focuses on three high-level topics in order to provide some answers to these questions (except question (c), which is usually answered through PA model calculations):

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| Topic 2 | Quantifying probabilities for scenarios – addresses question (b). [Contributors: **GSL** (international review), Technical Research Centre of Finland (**VTT**, review of practice in Scandinavia), and Nuclear Research Institute Řež (**NRI**, review of practice in the Czech Republic, review of formal use of expert judgement).] |
| Topic 3 | Trial of formal use of expert judgement for scenario conceptualisation – addresses question (d). [Contributor: Nuclear Research and consultancy Group (**NRG**), Netherlands.] |

The three topics were considered in three separate Milestone Reports (M2.2.C.1 to M2.2.C.3):

- A. Bassi and N. Devictor. PAMINA WP2.2C: Review of scenario development methodologies, M2.2.C.1, March 2008.
- D.A. Galson (editor), R.D. Wilmot, J.E. Morris, D. Reedha, H. Nordman and A. Vokal. PAMINA WP2.2C Topic 2: Quantifying scenario probability, M2.2.C.2, September 2009.
- J.B. Grupa. PAMINA WP2.2C Topic 3: Trial of formal use of expert judgement for scenario conceptualisation, M2.2.C.3, September 2009.

This Task Report provides guidance on the treatment of scenario uncertainties based on the material developed under Topics 1 to 3, and pointers to fuller explanations of the work conducted within Task 2.2.C.

Note that the work done under these Topics can be placed in the context of other task work within PAMINA where closely related studies have been conducted:

Topic 1: Review of scenario development approaches used in participating organisations within WP1.1 (RTDC-1), and work on scenario development within PAMINA in WP3.1 (RTDC-3).

Topic 2: Review of the treatment of uncertainty using probability within Task 2.1.C (Milestone Report M2.1.C.1) and the work on Total System Performance Assessment (TSPA) within Task 2.2.E (particularly the review work in Milestone Report M2.2.E.5) (RTDC-2), and reviews of the treatment of uncertainty in RTDC-1 (e.g., Milestone Report M1.2.1).

Topic 3: Review of expert elicitation approaches, techniques and issues (Milestone Report M2.2.A.3), and trial application for derivation of geochemical parameter values (Milestone Report M2.2.A.12) within Task 2.2.A (RTDC-2).

Note that it was not intended in Task 2.2.C to address all possible aspects of the questions addressed under Topics 1-3. This is particularly so for Topic 1, as significant work on this issue was also conducted under WP1.1 and WP3.1. However, each Milestone report in Task 2.2.C covers selected aspects of the identified issues.

Finally, note that the Task 2.2.C Topic 1 Milestone Report (M2.2.C.1) also considered issues of scenario implementation (model uncertainty), but we do not summarise that work here as it is outside the scope of Task 2.2.C. Work within Task 2.2.B of RTDC-2, reviews within WP1.1, and work within WP3.2, WP3.3 and all of RTDC-4 considered the issue of model uncertainty in considerably more detail. Interested readers should consult Milestone Report M2.2.C.1 directly.

The more detailed work referred to above is available on the PAMINA website (http://www.ip-pamina.eu/publications/reports/index.html) – this includes Milestone

Reports M2.2.C.1, M2.2.C.2 and M2.2.C.3, only the conclusions of which are summarised here.

## 1.2 Definitions

**Scenario**

There are several published definitions for the term "scenario". For example, according to the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) (NEA, 2001), a scenario "*specifies one possible set of events and processes, and provides a broad-brush description of their characteristics and sequencing.*" Swift *et al.* (1999) describe scenarios as "*a subset of the set of all possible futures of the disposal system that contains futures resulting from a specific combination of features, events and processes.*" Scenarios can thus be considered as broad descriptions of alternative futures of the waste disposal system, and can be used as the basis for assessments of the phenomena and components of the system, which are usually referred to as features, events and processes (FEPs).

**Probability**

Although there are different definitions of probability, in this report, probability is used in the context of the likelihood of occurrence of a scenario, event or process. Note that for the specific use of FEP probabilities for scenario development, it is important to distinguish between the probability of a FEP occurring (scenario uncertainty) and the use of probability to characterise uncertainties about a FEP (parameter value uncertainty). Both can be treated using either deterministic approaches or probabilistic approaches. Deterministic approaches to the treatment of parameter value uncertainty are normally paired with deterministic approaches to the treatment of scenario uncertainty. Probabilistic assessment of parameter value uncertainty can be paired with a deterministic approach or a probabilistic approach to the treatment of scenario uncertainty.

## 1.3 Report Structure

The remainder of this report is divided into the following sections:

- Section 2 summarises the Topic 1 review of scenario development methods.
- Section 3 summarises the case study and wider reviews undertaken for Topic 2 with respect to quantifying probabilities for scenarios.
- Section 4 describes the example formal expert elicitation methodology trialled in Topic 3, and provides guidance for the application of a qualitative approach to expert elicitation for other scenarios.
- Section 5 presents overall guidance on the treatment of scenario uncertainties in PA.
- Section 6 contains the list of supporting references.

# 2 Scenario Development

## 2.1 Introduction

Milestone Report M2.2.C.1 was produced by **CEA**, and addresses uncertainties associated with answering the following questions:

- What might happen to a geological disposal system?
- How might it happen?

Considerable uncertainties are associated with the answers to both of these questions owing to the long timescales associated with post-closure scenarios.

PAs are required to demonstrate that the disposal system is passively safe over a period of thousands of years or until safety indicators such as dose rate or risk reach their maxima. However, there is an international consensus that calculations should not be extended to times beyond those for which the assumptions underlying the scenarios, models and data used in the PA can be justified (NEA, 2004).

A PA must demonstrate that the disposal system (the waste form, the engineered barrier system (EBS) and the geological environment) effectively isolates, contains, and delays and attenuates any release of radionuclides to the biosphere over the assessment timeframe. In order to ensure that a PA is sufficiently comprehensive and robust, alternative futures for the evolution of the geological disposal system need to be considered. Most PAs aim to derive a limited number of these scenarios in a traceable and transparent way.

PAs can be structured according to the FEPs governing the evolution of the disposal system or according to safety functions. The post-closure period can be split into phases; as the disposal system evolves, some barriers can become less effective, such that different safety functions tend to dominate each phase (*e.g.* Figure 2.1).

The operational and post-closure phases of a geological disposal facility are not independent, as FEPs occurring prior to closure may impact on long-term safety of the facility. For example, weakening of the host rock during backfilling, sealing or closure may produce fractures which enable preferential groundwater flow pathways to develop. To incorporate these uncertainties, PAs use different scenarios to take into account events that may occur prior to or during closure of the facility, as well as those that may occur in the far future after closure of the facility.

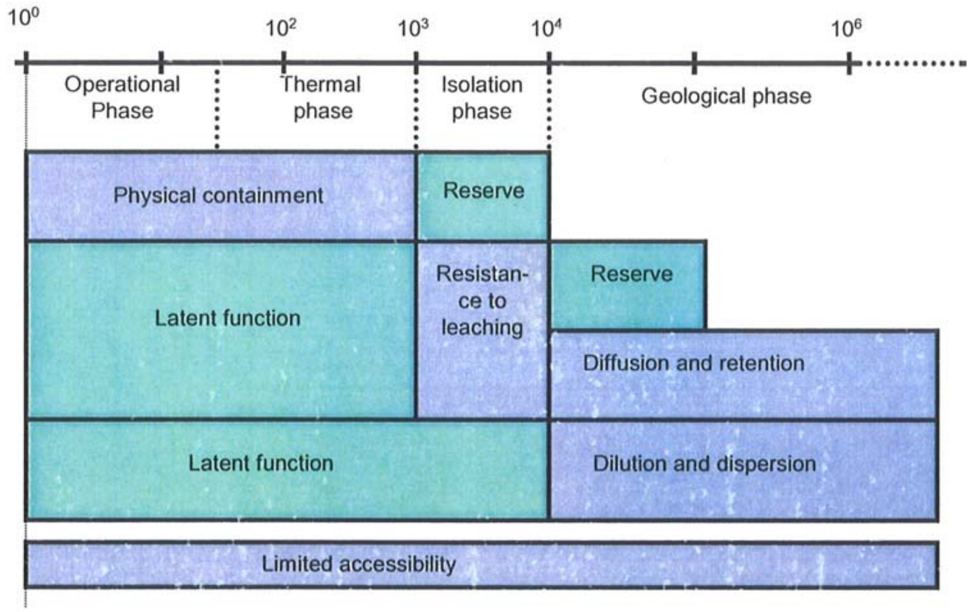


**Figure 2.1**: Safety functions and timeframes considered in the ONDRAF/NIRAS SAFIR 2 safety case.

The process by which scenarios are identified is known as "scenario development". A frequently used approach to scenario development is structured as follows (Galson and Khursheed, 2007):

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

(ii) Eliminate FEPs according to well-defined screening criteria.

(iii) Form scenarios from FEPs in the context of regulatory performance criteria.

(iv) 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.

Section 2.2 describes the identification and screening of FEPs, and Section 2.3 introduces the means of forming and specifying scenarios for consequence analysis. However, this latter topic is considered in more detail in Section 3.2 of this report. Section 2.4 presents conclusions of the work in Topic 1 of Task 2.2.C.

## 2.2 Identification and Screening of FEPs

Considering the above approach to scenario development, the first step is to identify a *comprehensive* list of FEPs that may significantly affect the performance of the disposal system. At an international level, generic FEP databases have been assembled over many years and used as a starting point.

FEPs are eliminated according to screening criteria, which are often based on the probability of occurrence and/or the severity of consequences, such that scenarios containing FEPs that are very unlikely to occur or that have relatively minor consequences are not analysed further. Although in the past some PAs have adapted generic international FEP databases to their specific requirements without formal screening criteria, the development of screening criteria is recommended because a structured and well-documented approach to the identification and screening of FEPs is the best way to justify the selection of a representative set of scenarios for analysis.

Conservative assumptions may lead to a decision to screen out favourable processes which have uncertainties that are difficult to quantify (*e.g.* dispersion or retention during transport through poorly characterised host rock).

The "screened in" FEPs are likely to cause either an initial release of radionuclides from the disposal facility or influence the behaviour of the radionuclides during transport to the biosphere. These FEPs can broadly be placed into three categories:

- Natural environment FEPs, which may influence the stability of the geosphere, such as climate change, erosion, earthquakes, volcanism or meteorite impacts. Apart from the latter, the relevance of natural FEPs and the related uncertainties are site-specific. Large uncertainties have to be considered on both the timescale and potential consequences of these FEPs.
- Waste and disposal facility FEPs, which are related to the waste, the EBS and the thermal-hydrological-mechanical-chemical (THMC) effects associated with the evolution of the disposal facility. These FEPs are often inter-related.
- Human activity FEPs, such as inadvertent intrusion into the disposal facility, initial material defects, or poor quality backfilling and sealing during closure of the facility.

Some FEPs are difficult to characterise owing to large and irreducible uncertainties, particularly those associated with potential future human intrusion. There is an international consensus that, rather than speculating on the likelihood and/or consequences of such events, a stylised approach should be adopted, where a set of credible scenarios is developed by expert judgement. The use of stylised scenarios for human intrusion is discussed in Milestone M3.1.12 (Morris *et al*., 2009).

Systematic approaches to identifying the FEPs of interest and their interactions have been developed, and in some cases implemented, in PAs. For example, in the UK, Nirex developed a systematic approach based on use of a so-called master directed diagram (MDD) to structure FEPs into an interconnected hierarchy, and to classify FEPs in terms of their likelihood of occurrence (Nirex, 1998a; Nirex, 1998b).

## 2.3 Scenario Formulation and Specification

Scenarios may be formulated using the "screened in" FEPs. A reference scenario describes the expected evolution of the disposal system "as designed", including all the expected FEPs and their interactions over time. The reference scenario includes the progressive degradation of the system (*e.g.*, resaturation of the disposal facility, corrosion, dispersion, etc.) and expected natural FEPs.

In order to consider uncertainties in future evolution of the disposal system, alternative evolution scenarios are also defined, which include less probable FEPs that may be expected to alter the normal evolution of the disposal system. Alternative scenarios may be based on the reference scenario with the addition of only one independent (scenario-initiating) FEP, such as early canister failure. Aggregation of multiple FEPs into scenarios other than the reference scenario is usually only performed in fully probabilistic PAs.

The screening and combination of FEPs should lead to the identification of a reference scenario and a reasonable number of alternative evolution scenarios to keep the required number of modelling calculations manageable, and to allow a clear presentation of the assessment.

Recent work on scenario development methodologies has led to increasing use of the concept of safety functions, i.e. those functions that the disposal system should fulfil during different time frames in order to achieve its long-term safety objective (see for example Figure 2.1). The aim in a scenario development methodology is to identify deviations from an expected evolution scenario, based on the failure of one or more safety functions. These potential failures can be 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.

The issue of scenario definition is considered in more detail in Section 3.2 of this report (Topic 2 of Task 2.2.C).

## 2.4 Summary Guidance on Scenario Development

Considerable uncertainties are associated with the question of what might happen to a geological disposal system. To ensure that a PA is comprehensive and robust, the consequence and likelihood of occurrence of alternative futures or scenarios need to be considered.

A structured and well-documented approach to the identification and screening of FEPs has frequently been used to justify the selection of a representative set of scenarios for analysis. Screening criteria, based on the probability of occurrence and/or consequences to the performance of the disposal system, should be used to screen out FEPs that are unlikely to occur or that have relatively minor consequences.

The “screened in” FEPs are used to formulate a reference scenario, including all expected FEPs, their interactions and developments over time, and a reasonable number of altered evolution scenarios. Stylised assumptions are used to treat FEPs with large and irreducible uncertainties, such as human intrusion.

# 3 Quantifying Scenario Probabilities

## 3.1 Introduction

Work under Topic 2 addressed the question of how FEP and scenario probability could be considered in PA and the safety case. The work is reported in Milestone Report M2.2.C.2., which was assembled by **GSL**, and is made up of contributions by **GSL** (international review), **VTT** (review of practice in Scandinavia), and **NRI** (review of practice in the Czech Republic, review of formal use of expert judgement).

Section 3.2 considers the definition and classification of scenarios, and Section 3.3 addresses four key questions on scenario probability:

1. Under what circumstances is probability estimation feasible?
2. What techniques are generally available for probability quantification?
3. Under what circumstances should probability estimation not be attempted and why?
4. For which scenarios is stylisation necessary and why?

Regulation on the topic of scenario probability is reviewed in Section 3.4, and conclusions concerning the estimation of scenario probability are presented in Section 3.5.

## 3.2 Scenario Definition

Scenarios are often assembled and classified based on their probability of occurrence and on the likelihood of the FEPs comprising the scenarios (NEA, 2005; Vigfusson *et al*., 2007):

- *A reference, main or "base case" scenario* represents the evolution of the disposal system within the expected range of uncertainty and in the absence of unlikely disturbances. In many assessments – and particularly where scenario uncertainty is treated deterministically – this scenario is assumed to have a probability of one.
- *Altered evolution scenarios* or alternative scenarios represent less likely, but still plausible, modes of disposal system evolution, and also describe how disturbances affect the evolution of the system.
- *Bounding scenarios* portray extreme events that are still within the range of realistic possibilities.
- *"What if" or residual scenarios* may be considered highly implausible or even impossible and given a nominal probability of zero. They explore the robustness of the system, such as complete failure of a confinement barrier for no identifiable reason.

- *Stylised scenarios* are essentially associated with future human actions (*e.g.*, intrusion) where few or no relevant data are available and there are very large uncertainties associated with describing the scenarios. Such scenarios can be considered a special type of altered evolution scenario, for which probability estimation is considered meaningless.

There are essentially three overarching methods for dealing with scenario probability in assessments, depending on the extent of quantification of the FEPs concerned:

- *Quantitative methods*, where all FEPs are represented numerically and event probability is an explicit part of the PA calculation, such as those methods employed in the probabilistic TSPA models used in the US Yucca Mountain and Waste Isolation Pilot Plant (WIPP) Projects – see below.

- *Qualitative methods*, where the likelihood of occurrence of FEPs is described qualitatively or semi-quantitatively, such as used in recent assessments in many European countries.

- *Non-consideration of probability,* especially where few or no relevant data are available and there are large uncertainties associated with describing the scenario. As noted above, this is normally the case for inadvertent human intrusion scenarios and, in such cases, plausible descriptions of human activities based on present-day human behaviour may be used in assessments, rather than attempting to develop descriptions of future human behaviour. It is not normally appropriate to assign probabilities, quantitative or otherwise, to these scenarios (ICRP, 1998).

Two main types of quantitative method to include scenario uncertainties in PA calculations 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.

2. Evaluation of a limited set of deterministically defined scenarios. Although individual scenarios are defined deterministically, scenario consequences may then be assessed probabilistically or deterministically. In this context, 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). In this approach, although the scenario development process still aims at identifying all relevant scenarios, there is not necessarily the same mathematical constraint that scenario probabilities must sum to one. This means, for example, that both the reference and some altered evolution scenarios can be conservatively assumed to have a probability of one. For less likely scenarios, a qualitative statement or quantitative estimate of scenario probability can be made, depending on the regulatory criteria concerned.

An intermediate partial probabilistic approach to evaluation of scenario uncertainty has been adopted in Sweden and Finland.

Scenarios including more than a single FEP that is not certain to occur are generally only considered in probabilistic assessments, although there is no reason why deterministic calculations should not include more than one of this type of FEP. There are two situations that can be considered for multiple "scenario-forming" FEPs: a situation in which the FEPs are independent; and a situation in which the FEPs are related or conditional upon each other. In the former case, the scenario probability is the product of the probabilities of the independent FEPs. In the latter case, it is the probability of the initiating FEP (e.g. glaciation) and the *conditional* probability of each subsidiary FEP (e.g. post-glacial faulting) that must be combined.

Where multiple FEPs are identified for consideration in one or more altered evolution scenarios, several approaches have been used for examining and quantifying combinations. The approach taken largely depends on the methodology used for scenario development, which varies considerably. Several tools have been used, either individually or in combination, to assist in the identification of FEPs for inclusion in scenarios, including:

- Event trees, logic diagrams, and related approaches that analyse alternative combinations of events and/or resulting system status (*e.g.* Figure 3.1).

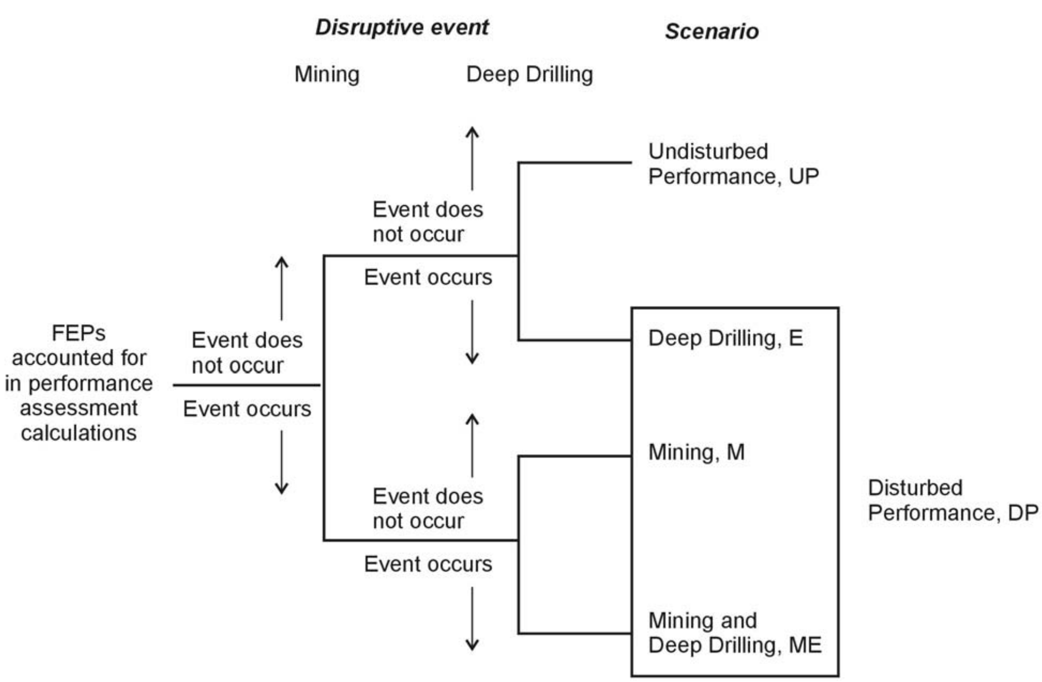


**Figure 3.1:** Example of a scenario logic diagram from the WIPP Compliance Certification Application (USDOE, 1996).

- Fault and/or dependency diagrams that set out in a hierarchical fashion the conditions and/or processes leading or contributing to an end point of interest.
- Interaction matrices that examine the dependency between selected FEPs.
- Safety function failure diagrams/tables that identify scenarios based on the ability of FEPs to lead to partial or total failure or bypassing of particular barriers.

Although all of these scenario development approaches can be used for identifying relevant FEPs to include in scenarios, only the first two support the combining of FEP probabilities and the definition of scenario probabilities for deterministic calculations, or provide a basis for simulating FEP interactions in probabilistic calculations. Audit tables that consider the representation of each FEP within the models or scenarios developed can help to identify omissions and evaluate biases.

## 3.3 Key Questions Regarding Scenario Probability

### 3.3.1 Question 1: Under what circumstances is probability estimation feasible?

In considering scenario uncertainty, we are specifically concerned with the treatment of uncertainty about when and how often particular FEPs (normally, specific events) included in the scenario occur, for which both deterministic and probabilistic approaches can be considered. Deterministic approaches to scenario uncertainty will generally use (best estimate or conservative) single values and ranges for FEP uncertainties. Probabilistic approaches to scenario uncertainty may be supported by a probabilistic representation of FEP uncertainties (e.g., the use of PDFs – the probability that a value occurs within a particular range of values), but also commonly use single values for FEP frequencies or rates.

It is possible to estimate a probability for scenarios, events or processes where:

- Sufficient data are available to use existing frequency data and projection into the future on the basis of these data is considered reasonable.
- The physical system is well understood and there are sufficient data to generate a realistic probability density function (PDF) describing the likelihood of occurrence of an event, or to otherwise estimate an event frequency.
- If the event or process is considered to be random, there are sufficient data to demonstrate randomness and there is a likelihood of future randomness.

Scenario probability has been considered quantitatively for a wide range of defining events and processes – for example:

- The US Yucca Mountain and WIPP probabilistic TSPAs use PDFs for parameters that characterise relevant FEPs to define the probability of occurrence of all scenarios considered.
    - ➢ WIPP: undisturbed performance, mining, drilling (USDOE, 1996).

  - Yucca Mountain: nominal case, early waste package/drip shield failure cases, igneous intrusion/eruption cases, seismic ground motion/fault displacement cases (USDOE, 1998).

- In Swedish and Finnish PA work, the reference case is assigned a probability of one and alternative scenarios are described as less likely or residual scenarios.
  - Estimating a numerical value for scenario probability is feasible for rock shear and, perhaps, for an initially defective canister. Both of these are examples of "less likely" scenarios. It is also considered possible to estimate the probability of an earthquake occurring that would be sufficiently large to cause damage to the canisters.
  - However, quantitative probabilities are only estimated where sufficient data are available. Where data are insufficient, a numerically conservative approach is taken. For example, the probability of a canister failure that follows from advective conditions in the buffer due to erosion of the buffer is currently set to one. The likelihood of advective conditions in the bentonite buffer is currently being studied, and it is hoped that a very low probability value can be demonstrated for this scenario in due course.

### 3.3.2 Question 2: What techniques are available for probability quantification?

In PAs where a separate reference case is considered, this case generally comprises all FEPs that are certain to occur. Thus, this case is given a probability of one and no additional probability quantification is required.

FEPs that are not certain to occur are included in one or more altered evolution or other less likely scenarios. In fully deterministic PAs, the probability of an altered evolution scenario may be set to one and the significance of conditional doses or risks judged using a qualitative assessment of likelihood. For example, the Swiss Opalinus Clay PA is fully deterministic: the reference case is given a probability of one, and separate cases are considered as variant scenarios, which are also given a nominal probability of one for the purposes of comparison with the reference case (Nagra, 2002).

Alternatively, if the probability of "scenario-forming" FEPs can be reasonably determined, the probability of the scenario can be defined. Whatever method is used to represent uncertainties, the probability of occurrence of most FEPs must be estimated on a site-specific and concept-specific basis. There are a number of theoretical approaches that can be used for determining probabilities (*e.g.*, Hunter *et al.,* 1992):

- *Axiomatic*. Axiomatic probabilities can be assigned if a logical analysis of the system shows that different states are equally likely, or have other defined probabilities. An example is the tossing of an unbiased coin, in which it is axiomatic that heads and tails have equal probabilities (ignoring the very unlikely case of the coin landing on its edge). There are very few if any examples of axiomatic probabilities for FEPs associated with disposal systems.

- *Frequentist*. With this approach, probabilities (frequencies) are derived from observations of how often an event has occurred in the past and/or in other locations. A large number of observations, or support from other lines of argument, is required to provide a statistically valid frequency or PDF of system states. Justification is also need to support projection of data on past events into the future, e.g., no anticipated changes in patterns of volcanism and earthquakes of given magnitudes.
- *Physical Model*. Sampling a model of the physical system using Monte Carlo simulations to generate a PDF of system states. This method can be used if the physical system is well understood and there are sufficient data to support a realistic simulation model.
- *Probability Model*. For events that are considered to occur at random, a probability model (e.g. Poisson) can be used directly in a simulation model or to derive a PDF of system states. For example, for a Poisson model, the probability of an event occurring is conditional on knowing the average occurrence rate and assuming that the times between successive events are independent. If there are insufficient data to support the assumption of randomness, or there are reasons to assume that future events will not occur randomly, then alternative assumptions regarding FEP probabilities are required.

Although there is a range of approaches for estimating FEP probabilities, there are many examples where there is insufficient information available to quantitatively estimate the probability of rare or non-periodic geological FEPs using these approaches. Where a quantitative estimate of the probability of occurrence for all FEPs identified as potentially significant is required to support fully probabilistic PAs (e.g., US Yucca Mountain and WIPP Projects), the above approaches must be supplemented by additional assumptions based on expert judgement. Review of formal expert elicitation techniques points to the crucial role played by an elicitation team formed by generalists and normative experts that must carefully analyse information from subject-matter experts to quantify their judgements.

In deterministic or combined deterministic and probabilistic PAs, it may be possible to use qualitative estimates about FEP probability and to undertake separate, conditional, assessments. Judgement is still required in these cases, not least in comparing results from a range of scenarios, but there is likely to be less reliance on subjective probability estimation methods.

In the Yucca Mountain and WIPP TSPAs, scenario probabilities were based on analysis of the frequency of previous events and expert judgement – natural events in the case of Yucca Mountain and human intrusion in the case of WIPP. The WIPP project is unique in that the regulator specified the human intrusion scenarios to be considered, the probability of mining scenarios, and the assumptions and method of calculation to use to estimate the likelihood and consequences of drilling scenarios, based on historical data. For Yucca Mountain, the regulator specified a stylised treatment of human intrusion that did not require consideration of scenario probability.

### 3.3.3 Question 3: Under what circumstances should probability estimation not be attempted and why?

The reasons why probability estimation may not be necessary or not worthwhile can be illustrated by reference to examples from several national programmes.

In the UK, the environment agencies provide specific guidance on quantifying uncertainties (including through estimation of probabilities) only where this is justifiable through statistical evaluation or other means (Environment Agency and NIEA, 2009). Uncertainties that cannot be reliably quantified should be addressed through conditional risk calculations and qualitative reasoning.

Usually, no attempt is made to quantify the probabilities of human-induced scenarios (the US WIPP project is an exception); siting requirements ensure that the likelihood of occurrence of such scenarios is minimised. This approach is consistent with the position of the International Commission on Radiological Protection (ICRP) that it is inappropriate to include the probability of future human actions in a quantitative performance assessment for comparison with dose or risk constraints (ICRP, 1998). Instead, the consequences of one or more stylised scenarios should be considered to evaluate the resilience of the disposal system design to such events. In all programmes, the assessment of intentional human intrusion is specifically excluded from assessment.

In the Czech programme, the premature failure of the proposed carbon steel canisters after hundreds of years does not significantly affect the performance of the disposal system, and it is therefore assumed that hidden initial canister defects would have no significant effect on PA results. In such cases, there may be little point in quantification of scenario probability, which can be conservatively taken as one.

Also, the probability of occurrence of natural events that could significantly affect the disposal system performance is considered to be negligible in the Czech programme, as regulatory siting requirements rule out consideration of areas where such events could occur. Where probabilities are extremely low and siting has already been aimed at minimising probability, there may be limited value in detailed quantification.

Residual or “what if” scenarios have a very low probability of occurrence and are generally assigned a probability of zero. They are used to illustrate the robustness or significance of barriers, or the overall robustness of the disposal system.

### 3.3.4 Question 4: For which scenarios is stylisation necessary and why?

Stylised assumptions are generally applied to scenarios involving future human actions because of the large uncertainties involved in predicting how human society will evolve in the far future. However, there are some notable differences between programmes that result from differences in the applicable regulations:

- Regulators in Europe consider that the developer/operator of the disposal system should use stylised assumptions to explore future human action scenarios (Vigfusson *et al.*, 2007). For example, in the UK, the environmental regulators consider that, where few or no relevant data are available, arbitrary assumptions may be made that "*are plausible and internally consistent, but err on the side of conservatism*" (Environment Agency and NIEA, 2009).

- In contrast, for the US WIPP project, the regulator specified the assumptions and calculation processes to be used in developing human intrusion scenarios, based on historical data, and a stylised approach was not necessary.

## 3.4 Regulatory Perspective on the Estimation of Scenario Probabilities

There are contrasting regulatory perspectives on assigning or estimating scenario probabilities in the US and Europe:

- In the US, regulations tend to be prescriptive, specifying that repository developers/operators must conduct probabilistic assessments and, in the case of the WIPP for example, the assumptions to be made and the methods to be used in developing disturbed (mining and drilling) scenarios (US EPA, 1996).
- In Europe, repository developers/operators are encouraged to develop a limited number of illustrative scenarios to enhance understanding of the disposal system and its evolution. Both deterministic and partial probabilistic methods are accepted by the regulators, but fully probabilistic TSPAs alone are considered an unsatisfactory approach for decision making, mainly because probabilities need to be generated for every FEP, including those which cannot readily be quantified, and aggregated presentation methods may hide judgements and assumptions.

  In the UK, the environment agencies recommend that uncertainties that cannot be readily quantified be explored through the use of separate risk assessments for each such scenario, by assigning each a nominal probability of one. Scenarios involving highly uncertain future events and human actions should be treated separately and may be assessed qualitatively (Environment Agency and NIEA, 2009).

## 3.5 Summary Guidance on Probability Estimation

Given the large uncertainties involved, the main consideration in the assignment of probabilities to events, processes and scenarios is credibility. Some considerations that will enhance the credibility of probability estimates include:

- Careful interpretation of data in the geological and/or historical record.
- Careful explanation that most scenario probabilities should be considered as "degrees of belief" rather than relative frequencies. If frequency data are available, the analysis will be conditional on the assumptions regarding the use of such data to make projections into the far future.
- The use of formal expert judgement techniques where the safety case outcome relies significantly on assessments of scenario probability.

- Use of modelling approaches to simplify assessments, and clear representation of the factors that could increase or reduce any estimate of scenario probability.
- Avoidance of probability estimation where insufficient information is available, or where assessment outcomes do not depend on this probability, or where siting has already explicitly considered the issue and there is nothing that can be done to reduce the probability further.

# 4 Formal Use of Expert Judgement in Scenario Conceptualisation

## 4.1 Introduction

Work under Topic 3 was conducted by **NRG**, and it addressed the question:

- *How can stylised scenarios (i.e. future human actions scenarios) be conceptualised?*

A trial of the formal use of expert judgement was conducted to improve the basis for conceptualisation of a stylised "abandonment" scenario for a geological disposal facility. The methodology, results and conclusions of the trial are described in Milestone Report M2.2.C.3.

The abandonment scenario is of particular interest to the Dutch programme (although does not tend to receive much attention in other national programmes). The scenario is briefly described in Section 4.2, followed by a summary of the expert judgement methodology in Section 4.3. Guidance for the application of a qualitative approach to expert elicitation for other scenarios is given in Section 4.4.

As noted in Section 1, additional work within PAMINA trialling expert judgement elicitation techniques has been undertaken within the context of Task 2.2.A on parameter uncertainty (M2.2.A.12, Bolado *et al*., 2009).

## 4.2 Stylised Scenario: Abandonment of a Geological Disposal Facility

The abandonment scenario considers the case when a geological disposal facility is abandoned before proper closure owing to unforeseen circumstances. Events that could lead to abandonment without proper closure are major economic problems, war, national disasters, and mining disasters. Previous Dutch assessment studies assumed that abandonment would lead to the following chain of events:

(i) Flooding of unsealed tunnels.

(ii) Dissolution of soluble parts of the waste in the water.

(iii) Advective flow and diffusion of radioactively contaminated water through the disposal facility.

(iv) Radioactive material reaching any overlying aquifers and the biosphere.

(v) Exposure of humans to radioactive material.

Attempts have not previously been made to confirm the assumed sequence of events listed above or to obtain further insights from mining technology, geology and hydrogeology that are potentially relevant to the scenario.

## 4.3 Methodology for Elicitation of Expert Judgement

A formal procedure for the elicitation of expert judgement was prepared by **NRG**, which divided the process into 15 steps (Table 4.1).

**Table 4.1**: Protocol for expert elicitation.

| Step | Description | Comment |
|---|---|---|
| 1 | Definition of case structure | The case structure provides the frame for the panel of experts specifying all issues taken into consideration. |
| 2 | Identification of target variables | All model parameters to be assessed by experts are identified and listed. A formal procedure is used to select the most important ones for expert elicitation. |
| 3 | Identification of query variables | The target variables as defined under step 2 may not be appropriate for direct elicitation. The questions are formulated consistent with the way in which an expert represents the relevant information in his/her knowledge base. |
| 4 | Identification of performance variables | Performance variables are supported with evidence unknown to the experts. |
| 5 | Identification of experts | An expert is regarded by others as being knowledgeable about the subject. |
| 6 | Selection of experts | The selection of experts takes place through a formal procedure with a selection (or nomination) committee, or by the project staff. |
| 7 | Definition of elicitation document | This document contains the following information:<br>• exact description of the questions;<br>• necessary explanation of each question;<br>• additional remarks on what is to be included or excluded;<br>• the format in which the assessments need be provided by the experts. |
| 8 | Dry run exercise | One or two persons (not the selected experts) experienced in the field of interest are asked to provide comments on the case structure and the elicitation document. |
| 9 | Expert training session | The experts are trained in understanding the issues and in providing the answers in the requested format. |
| 10 | Expert elicitation session | Each expert is interviewed individually. In such sessions a 'substantive' expert, who is experienced in the expert's field of interest, is present as well. |
| 11 | Combination of expert assessments | The results are treated anonymously. The responses of the experts must be combined in a way that agreement between the responses, and conflicts or discrepancies, can be identified. |
| 12 | Discrepancy and robustness analysis | Discrepancies in the responses are reviewed in order to find the reason for the discrepancy. |

| Step | Description | Comment |
|---|---|---|
| 13 | Feedback | The results are treated anonymously, and the experts' names are only used in passages such as the composition of the panel, if the experts agree. Each expert is given access to his/her assessment and to the way the responses have been combined. |
| 14 | Post-processing analyses | The aggregated results are post-processed if the target variable differs from the query variable. |
| 15 | Documentation | All relevant information and data are formally documented. |

The following strategy was developed to formulate questions that are consistent with the way in which an expert represents the relevant information in his/her knowledge base:

- The experts should not have to reproduce knowledge that is already known to the substantive experts, so questions like "How does xxx depend on yyy?" were replaced by "Do you agree that xxx depends on yyy as follows: (...)?"

- The experts do not have to perform calculations if they can provide sufficient information for the substantive experts to do the calculations. Questions like "How long does it take for xxx to move from yyy to zzz?" were replaced by "Which processes and phenomena determine the speed at which xxx can move?".

The experts were encouraged to make suggestions that may result in improvement of the design of the repository and/or the selection of the site where a repository may be built. This resulted in an additional question being posed to the experts.

The results of the expert judgement elicitation exercise largely confirmed the previously assumed chain of events for the abandonment scenario, thereby building confidence in application of these assumptions to future Dutch PAs. The experts distinguished two variants of the abandonment scenario:

- Gradual flooding of the disposal facility from the normal inflow of water (assumes that the underground pumps are not working). Depending on local site characteristics and the facility design, it could take years or decades for the facility to become completely flooded.

- Failure of the shaft lining, leading to the possibility of complete flooding in days to weeks. This variant is more likely if a loss of institutional control is preceded by a period of insufficient institutional control during which the maintenance of the facility is poor.

The experts pointed out that if abandonment occurs during the period in which waste is still being emplaced in the disposal facility, it is likely that one or more disposal cells containing waste containers will not be completely sealed. This could lead to more rapid access of groundwater to waste containers than would otherwise be the case.

In addition, the experts pointed out that if there is ongoing institutional control at the time of abandonment, an attempt to recover the facility will eventually be undertaken, with a high likelihood of success. Therefore, in the case of ongoing institutional control, the abandonment scenario is very unlikely.

## 4.4 Summary Guidance on Application of a Qualitative Approach to Formal Expert Elicitation

This trial demonstrated that the elicitation procedure developed for obtaining statistical distributions for quantitative target variables through expert judgement is also useful for qualitative target variables. Agreements between the experts might be used as a way to improve the basis for a given scenario, while differences might be resolved either by widening the uncertainty related to the scenario (to cover different experts' views), or by iterative expert elicitation steps.

For quantitative target variables, the steps required to aggregate the results of the experts are straightforward (although this can be mathematically complicated). For qualitative target variables, aggregation of the results is less straightforward. During analysis of the results, it was proposed that the responses of the experts should be added to the relevant FEPs in the FEP database used for scenario development. This was not foreseen at the start of the trial. For future expert judgement studies for scenario development, it is recommended that the procedure ensures that the responses of the experts are recorded in the FEP database. This additional information in the FEP database can be evaluated when the FEPs are used in scenario development, and at that time it can be decided which expert's view is most applicable to the scenario(s) under consideration.

For quantitative target variables, it is recommended that a scheme is developed that also ensures that the qualitative arguments of the experts are available when the results are evaluated for use. This may be a better approach than weighting the experts' using a weighting scheme that may not be appropriate to the situation in which the quantitative results are eventually used.

# 5 Overall Summary Guidance

Guidance for the treatment of scenario uncertainty has been obtained from the three Milestone Reports developed under Task 2.2.C.

**Scenario Development**

- Considerable uncertainties are associated with the question of what might happen to a geological disposal system. To ensure that a PA is comprehensive and robust, the consequence and likelihood of occurrence of alternative futures or scenarios need to be considered.
- A structured and well-documented approach to the identification and screening of FEPs has frequently been used to justify the selection of a representative set of scenarios for analysis. Screening criteria, based on the probability of occurrence and/or consequences to the performance of the disposal system, should be used to screen out FEPs that are unlikely to occur or that have relatively minor consequences.
- The screened-in FEPs are used to formulate a *reference* or base-case scenario, including all expected FEPs, their interactions and developments over time, often considered in discrete periods after closure of the disposal facility. The reference scenario describes the normal evolution of the disposal system within the expected range of uncertainty, and is assumed to have a probability of one.
- *Altered evolution scenarios* or alternative scenarios are less likely than the reference scenario, and these are developed on the basis of perturbations of the normal evolution of the disposal system.
- *Bounding* scenarios portray extreme events that are still within the range of realistic possibilities.
- *"What if"* or residual scenarios may be considered highly implausible or even impossible, and are given a nominal probability of zero.
- *Stylised* scenarios are used to treat inadvertent human intrusion events that involve large and irreducible uncertainties.

**Quantifying Scenario Probabilities**

Given the large uncertainties involved, the main consideration in the assignment of probabilities to events, processes and scenarios is credibility. Some considerations that will enhance the credibility of probability estimates include:

- Careful interpretation of data in the geological and/or historical record.
- Careful explanation that most scenario probabilities should be considered as "degrees of belief" rather than relative frequencies. If frequency data are available, the analysis will be conditional on the assumptions regarding the use of such data to make projections into the far future.
- Use of modelling approaches to simplify assessments, and clear representation of the factors that could increase or reduce any estimate of scenario probability.

- Avoidance of probability estimation where insufficient information is available, or where assessment outcomes do not depend on this probability, or where siting has already explicitly considered the issue and there is nothing that can be done to reduce the probability further.
- The use of formal expert judgement techniques where the safety case outcome relies significantly on assessments of scenario probability.

**Formal Use of Expert Judgement**

The elicitation procedure developed for obtaining statistical distributions for quantitative target variables through expert judgement is also useful for qualitative target variables. Agreements between the experts might be used as a way to improve the basis for a given scenario, while differences might be resolved either by widening the uncertainty related to the scenario (to cover different experts' views), or by iterative expert elicitation steps.

It is suggested that the responses of the experts for qualitative target variables are recorded in the relevant FEPs in the FEP database used for scenario development. For future expert judgement studies for scenario development, it is recommended that the procedure states that the responses of the experts will be recorded in the FEP descriptions. When the FEPs are used in scenario development, it can be decided which expert's view is most applicable to the scenario(s) under consideration.

For quantitative target variables, it is recommended that a scheme is developed that ensures that the qualitative arguments of the experts are available when the results are evaluated for use. This may be a better approach than weighting the experts' views using a scheme that may not be appropriate to the situation in which the quantitative results are eventually used.

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