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

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QUANTIFYING SCENARIO PROBABILITY
MILESTONE (N°: M2.2.C.2)

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RE	Restricted to a group specified by the partners of the [PAMINA] project	
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Foreword

The work presented in this report was developed within the Integrated Project PAMINA: **P**erformance **A**ssessment **M**ethodologies **IN** **A**pplication to Guide the Development of the Safety Case. This project is part of the Sixth Framework Programme of the European Commission. It brings together 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.

Milestone M2.2.C.2
Version 1.0

PAMINA WP2.2C Topic 2: Quantifying Scenario Probability

September 2009

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PAMINA WP2.2.C Topic 2: Quantifying Scenario Probability

Report History

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

Draft 1.0 (January 2008) contained an outline for the report and a completed Introduction (Section 1).

Draft 2.0 (February 2009) contained the input from VTT and NRI.

Draft 3.0 (August 2009) was a full review draft and contained the input from GSL, plus a revised Introduction and Summary.

This is the final Version, and accounts for comments received from C. Hansen (SNL) and M. Poole (NDA) on Draft 3.0.

PAMINA WP2.2C Topic 2: Quantifying Scenario Probability				
Version:	Date:	Lead Author: D.A. Galson	Reviewed by: R.D. Wilmot	Approved by: D.A. Galson
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Executive Summary (GSL)

This document reports on activities performed within Topic 2 of PAMINA WP2.2C. WP2.2C aims to evaluate methods for the treatment of uncertainties associated with scenarios, that is, uncertainty about what might happen to the disposal system in the future. Topic 2 focuses on the quantification of scenario probabilities. This report has been assembled by Galson Sciences Limited (**GSL**), and is made up of contributions by GSL (international review), Technical Research Centre of Finland (**VTT**, review of practice in Scandinavia), and Nuclear Research Institute Řež plc (**NRI**, review of practice in the Czech Republic).

This report considers the definition and classification of scenarios, and then 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 and features is stylisation necessary and why?

The report also reviews regulation on the topic of scenario probability.

Scenario definition and classification

Scenarios can 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). 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 (single value) approaches or probabilistic (sampling) approaches.

Scenarios are often classified based on their probability of occurrence and on the likelihood of the FEPs comprising the scenarios:

- *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* 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.

The probability of scenarios can be evaluated and discussed in a safety case in one of three ways: quantitatively, qualitatively, or not at all in the case of stylised scenarios.

Question 1: Under what circumstances is probability estimation feasible?

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 Waste Isolation Pilot Plant (WIPP) probabilistic Total System Performance Assessments (TSPAs) use PDFs for parameters that characterise relevant FEPs to define the probability of occurrence of all scenarios considered.
    - WIPP: undisturbed performance, mining, drilling.
    - Yucca Mountain: nominal case, early waste package/drip shield failure cases, igneous intrusion/eruption cases, seismic ground motion/fault displacement cases.
- In the Swedish and Finnish performance assessment (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.

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.

Alternatively, if the probability of "scenario-forming" FEPs can be reasonably determined, the probability of the scenario can be defined. Approaches that can potentially be used to determine FEP probabilities include:

- Derivation from observations of past events and existing conditions.
- Sampling a model of the physical system using Monte Carlo simulations.
- Use of a probability model (e.g. Poisson).
- Use of expert judgement, ideally through a well developed expert elicitation process, particularly where data are scarce or where safety case results depend strongly on probability. 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.

Similar approaches can be used to define PDFs of FEP characteristics for use in probabilistic calculations.

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.

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

We illustrate the reasons why probability estimation may not be necessary or not worthwhile via 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. Uncertainties that cannot be reliably quantified should be addressed through conditional risk calculations and qualitative reasoning.

No attempt is usually 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. 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.

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. 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*".

- 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.

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.
- 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.

Overall conclusion

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.

Contents

PAMINA WP2.2.C Topic 2: Quantifying Scenario Probability

1 Introduction (GSL)

1.1 Background and Aims

PAMINA (**P**erformance **A**ssessment **M**ethodologies **IN** **A**pplication to Guide the Development of the Safety Case) is an Integrated Project funded by the Sixth Framework Programme of the European Commission. The work is organised in four Research and Technology Development Components (RTDCs) and one additional component dealing with knowledge management and dissemination of knowledge. 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 performance assessment (PA) and safety case development.

Within RTDC2, Work Package 2.2C (WP2.2C) aims to evaluate methods for the treatment of uncertainties associated with scenarios, that is, uncertainty associated with what might happen in the future to a disposal system. Within WP2.2C, work is focusing on three topics:

Topic 1 Review of scenario development methodologies with respect to treatment of uncertainty and the issue of comprehensiveness (PAMINA Milestone M2.2.C.1).

Topic 2 Quantifying probabilities for scenarios (this report, PAMINA Milestone M2.2.C.2).

Topic 3 Trial of formal use of expert judgement for scenario conceptualisation (PAMINA Milestone M2.2.C.3).

The topics are covered by performing detailed reviews and conducting research by means of case studies selected from the programmes of participating organisations and from wider review. Individual Topic Reports will be drawn together into a Task Report by GSL (PAMINA Deliverable D2.2.C.1).

This Topic Report, compiled by GSL, reviews approaches to quantifying scenario probabilities and case studies from several countries, and formulates guidance for the treatment of uncertainties.

1.2 Definitions

There are several published definitions for the term “scenario”. 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).

Normally the possibility of the occurrence of one or more particular events is used to define alternative scenarios, but we often use the term "FEP" in this report for the sake of greater generality.

Scenario uncertainty arises in assessments because of the need to demonstrate that the set of FEPs considered in an assessment is comprehensive, and because of the difficulty of quantifying the likelihood of occurrence of scenario-defining FEPs. The issue of comprehensive is considered within Topic 1 of WP2.2C (Bassi and Devictor, 2008) and elsewhere within PAMINA. This report deals with the issue of scenario probability.

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 Total System Performance Assessment (TSPA) models used in the US Yucca Mountain and Waste Isolation Pilot Plant (WIPP) Projects.
- *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. 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).

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 (TSPA) approach to the treatment of scenario uncertainty.

1.3 Objective and Scope

The aim of this document is to provide answers to the following questions through generic research and selected case studies:

1. Under what circumstances is probability estimation feasible?
2. What techniques are 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?

An additional aim is to outline regulatory considerations on the issue of scenario probability.

This report for PAMINA WP2.2C Topic 2 is made up from contributions by **GSL**, **VTT** (Technical Research Centre of Finland) and **NRI** (Nuclear Research Institute Řež plc), and concludes with a section that draws together the findings from the contributions into a set of guidelines concerning the use of probability to treat scenario uncertainty.

1.4 Structure of Report

The report is structured as follows:

- Section 2 reviews approaches to quantifying scenario probability, using examples from several countries, and selected regulation on this topic (GSL international review).
- Section 3 reviews the Swedish KBS-3 geological disposal concept, and methods for assigning quantitative and qualitative probabilities to scenarios from the Swedish and Finnish programmes (VTT case studies).
- Section 4 discusses scenario development and probability estimation methods with respect to the Czech programme, and evaluates methods for quantification of scenario probability based on formal expert judgement techniques (NRI case study and research).
- Section 5 summarises the review and case study results, and concludes with guidelines concerning the use of probability to treat scenario uncertainty (GSL).
- Section 6 lists the references used in the report.

2 Review of Techniques for Estimation of Scenario Probability and Selected Examples of Application and Regulation (GSL)

GSL has carried out a review of approaches to quantifying scenario probabilities, and has illustrated the approaches with examples from several countries. Section 2.1 provides an outline of available techniques for the estimation of scenario probabilities. Examples of qualitative and quantitative estimation of scenario probabilities in different PAs are discussed in Section 2.2. Regulatory attitudes to scenario probability are illustrated in Section 2.3. A summary of the reviewed approaches is provided in Section 2.4.

2.1 Estimation and Use of Scenario Probabilities

In order to ensure that a PA is sufficiently comprehensive and robust, alternative futures for the evolution of the disposal system need to be considered. If adopting a scenario-based approach, most PAs aim to derive a limited number of scenarios in a traceable and transparent way. Scenario development typically involves four basic steps (Galson and Khursheed, 2007):

- Identification and classification of all FEPs that may affect the performance of the disposal system.
- Screening of FEPs using well-defined screening criteria.
- Aggregation of FEPs to form scenarios.
- Selection of scenarios for consequence analysis (for comparison with dose, risk or alternative performance measure).

Following an explanation of scenario classification terminology, those steps which are involved in the estimation of FEP and scenario probabilities are discussed below (Sections 2.1.1 and 2.1.2). Estimates of scenario probabilities can be used to screen FEPs and calculate risk performance measures (Section 2.1.3).

Scenario classification

Scenarios are often 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 in the absence of unlikely disturbances. In many assessments, this scenario is assumed to have a probability of one.
- *Altered evolution scenarios* represent *less likely*, but still plausible, modes of disposal system evolution, such as more rapid barrier degradation than was expected. They also describe how disturbances affect the evolution of the system. The probability of occurrence of a particular scenario may be estimated using the methods discussed below, or the consequences of the scenario may be

qualitatively compared with the reference case, but without a quantitative estimate of probability.

- *Bounding scenarios* portray extreme events that are still within the range of realistic possibilities, such as an extreme ice-age or a major seismic event. Probabilities for this type of scenario are difficult to define and the significance of bounding scenarios must generally be assessed qualitatively.
- *"What if" or residual scenarios* do not aim to be realistic, but are used to explore the robustness of the system, such as complete failure of a confinement barrier for no identifiable reason. No quantitative assessment of their significance can be made as they are considered impossible, with a nominal probability of zero.
- *Stylised scenarios* are essentially associated with future human actions (e.g., intrusion) for which 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. As already noted in Section 1, it is not normally appropriate to assign quantitative probabilities to these scenarios for comparison with dose or risk constraints (ICRP, 1998).

Note that the use of stylisation to conceptualise human intrusion scenarios is not to be confused with the use of stylisation to undertake consequence assessment. Human intrusion is an external influence on the disposal system. Once the scenario description has been stylised, there may be extensive data available to model the potential impact of the scenario. However, for some components or characteristics of the disposal system, a stylised assessment approach must be taken. In particular, the evolution of the surface environment (biosphere) – a part of the disposal system in all scenarios – must be assessed using stylised assumptions, because of the large uncertainties involved in predicting how the biosphere will evolve in the far future.

2.1.1 Estimation of FEP Probabilities

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 probability density functions (PDFs) – the probability that a value occurs within a particular range of values), but also commonly use single values for FEP frequencies or rates.

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 several theoretical approaches that can be used for determining event 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 are several 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. How these and other FEPs for which there is a lack of observations are treated depends in large part on regulatory expectations (see Section 2.3).

Where a quantitative estimate of the probability of occurrence for all FEPs identified as potentially significant is required to support fully probabilistic TSPAs (e.g., US Yucca Mountain and Waste Isolation Pilot Plant (WIPP) Projects, discussed in Sections 2.2.1 and 2.3.3), the above approaches must be supplemented by additional assumptions based on expert judgement 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. Such methods have been criticised as potentially subject to manipulation or bias, whether inadvertent or deliberate, because they depend on individual judgement to a greater or lesser degree. A review of expert judgement techniques to assign scenario probability is provided in Section 4.3, and an example of expert elicitation with regard to scenario conceptualisation has been undertaken as Topic 3 within WP2.2C.

2.1.2 Estimation of Scenario Probabilities

In discussing scenario probabilities, it is important to distinguish the assessment approach and the type of scenario concerned:

- Deterministic approaches to scenario uncertainty are generally based on conceptual or *descriptive scenarios* (e.g., reference scenario and a limited number of altered evolution scenarios), each with a probability of occurrence discussed either quantitatively or qualitatively. Although the calculated doses from different scenarios may not be rolled into a single estimate of risk, separate scenario-by-scenario consideration of impact can lend clarity and transparency to decision making.
- In probabilistic approaches to scenario uncertainty, there may be only one or two descriptive scenarios (e.g., undisturbed and disturbed performance scenarios), which are evaluated by means of a very large number of *calculational scenarios*, each with different characteristics typically defined by sampling from the relevant PDFs. The probability of each calculated performance measure is related to the mathematical sampling scheme used. For example, in unbiased sampling schemes, such as simple random sampling and Latin Hypercube Sampling (LHS), each of the calculational scenarios will have the same probability (the inverse of the number of simulations) and will contribute equally to calculated dose or risk.

Descriptive scenarios

Where the reference scenario is assumed to have a probability of one, all of the FEPs that occur within this scenario must also be assumed to have a probability of one. Any FEP that is not certain to occur (i.e., to have a probability significantly less than one) must form part of an altered evolution (or other less probable) scenario.

If an altered evolution scenario is based on the reference case with the addition of a single uncertain FEP (or on the assumption that a reference case FEP has a probability significantly less than one), then the scenario probability will be the same as the FEP probability. Scenarios including more than a single FEP that is not certain to occur are generally only considered in probabilistic approaches to scenario uncertainty, although there is no reason why deterministic approaches should not include more than one FEP of this type.

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 between projects, e.g., as a result of differing regulatory requirements and the stage of development of the project. 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 (see below).
- 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.

An example of an event tree approach is given in Figure 2.1, which illustrates the scenario development approach used at WIPP.

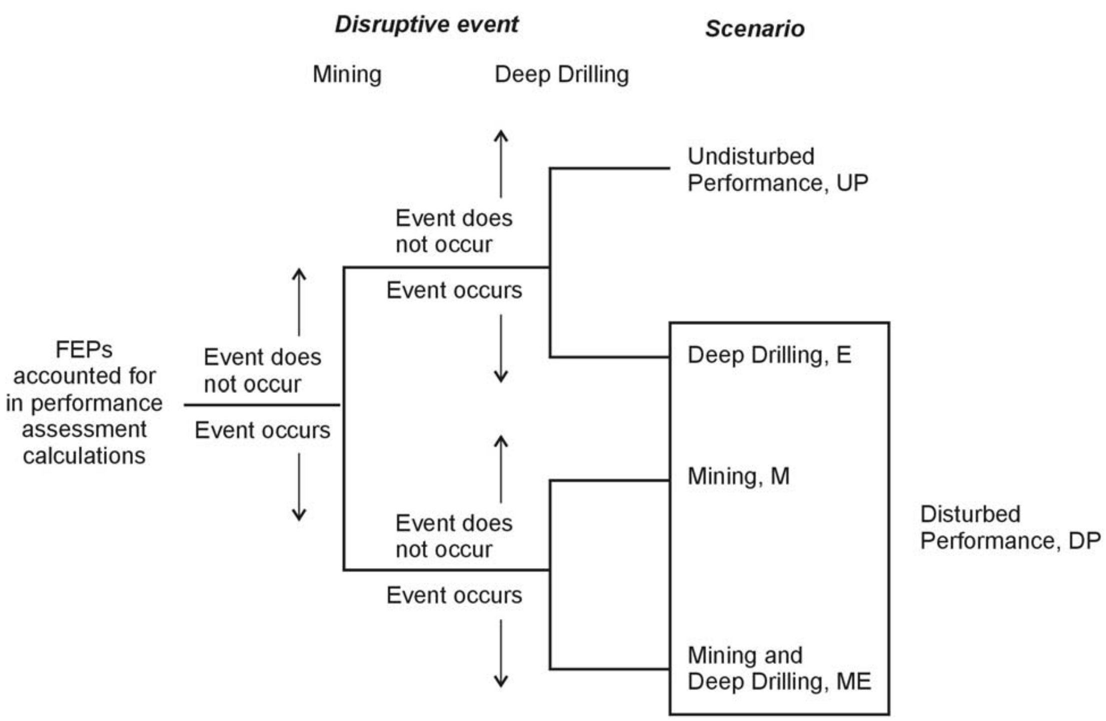

Figure 2.1: Example of a scenario logic diagram from the WIPP Compliance Certification Application (from US DOE, 1996).

When events have fixed probabilities, event trees can be extended to Markov models. A Markov model assumes that at each future change of state (transition), there is a fixed probability associated with each subsequent state represented by a branch of an event tree. Multiplication of probabilities along each branch of the event tree yields the probabilities of the resulting end-member scenarios.

Approaches such as Markov models do not ensure that all possible scenarios are identified (because there may be other states not included), and there are assumptions about the order of transitions and fixed transition probabilities. Nevertheless, such approaches can provide useful information about the relative probabilities of scenarios that can be used for assessment calculations. More complex, Markov-based models can be constructed, but are unlikely to be supported by available information. In general, all of the techniques rely on expert judgement to ensure that the models reflect the state of knowledge and uncertainties. Given the large uncertainties involved, scenario probabilities should generally be considered as “degrees of belief” rather than as (verifiable) relative frequencies.

In deterministic approaches to scenario uncertainty, although the scenario development process still aims at identifying all relevant scenarios, there is not necessarily a requirement that scenario probabilities be rigorously quantified. 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 (e.g. see Section 2.2.2). This approach has the advantage of not placing undue emphasis on estimates of scenario probability that are considered to contain significant uncertainty.

Calculational scenarios

In deterministic approaches to scenario uncertainty, calculational scenarios generally correspond to the descriptive scenarios. There may be a significant number of additional calculations undertaken of variants or for sensitivity studies, but these do not affect the assignment of scenario probabilities. In deterministic approaches, a single value of probability is assigned to a disruptive event or scenario, where probability is evaluated quantitatively.

In contrast, in the TSPA approach, calculational scenarios are typically generated by sampling the PDFs that characterise all of the FEPs included in the descriptive scenarios. For unbiased sampling methods such as simple random sampling and LHS, each of the calculational scenarios will be equally likely, with a probability determined by the number of simulations performed. This means that the scenario probability represented by a particular combination of FEP characteristics will effectively decrease if more simulations are performed, as a result of a finer division of all the possible combinations (i.e., the particular combination of characteristics is representative of a smaller number of possible combinations). TSPAs should demonstrate numerical convergence of key results by increasing sample size – for the consideration of scenario uncertainty, this is likely to mean testing the stability of calculated performance measures to an increase in the number of calculational scenarios.

Probabilistic assessments may include both "undisturbed" and "disturbed" performance as descriptive scenarios. This may be done to satisfy regulatory criteria and/or to allow the consequences of undisturbed performance to be examined in more detail. In terms of calculational scenarios in a TSPA approach, a number of the simulations of disturbed performance will not sample any of the disruptive FEPs and will thereby correspond to undisturbed performance. Depending on the probability of the disruptive FEPs, the number of simulations of undisturbed performance may be relatively small and therefore insufficient to adequately characterise undisturbed performance within an otherwise "converged" value of the performance measure. In such cases, a separate, more detailed probabilistic calculation of the undisturbed performance scenario may be performed. Methods for demonstrating numerical convergence may differ for undisturbed and disturbed scenarios, as the number of uncertain quantities involved in scenario definition may differ.

Scenario subsumption

Given a potentially large number of scenarios, it is necessary to have a systematic process for producing a realistic assessment that does not neglect any scenario that could make a significant contribution to the overall risk associated with a disposal facility, while still reducing the number of scenarios to be considered in detail to a manageable level. United Kingdom Nirex Limited (Nirex) developed an approach to dealing with scenarios in performance assessment that they term scenario "subsumption" (Billington and Bailey, 1998). In the Nirex approach, the aim is to treat explicitly only those scenarios that cannot be "subsumed" into a scenario of higher *conditional* risk (scenario probability assumed to be one). This approach leads to a reduction in the number of scenarios for which detailed consideration of probability may be necessary within a risk-based regulatory framework, as exists in the UK.

2.1.3 Use of FEP and Scenario Probabilities

Screening of FEPs

The screening criteria for FEPs 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. FEP screening is an iterative process through the assessment cycle, with an uncertainty analysis based on probability estimates potentially identifying FEPs to be included, or screened out of, subsequent assessments. Probabilistic consequence analysis is discussed further in the reports from PAMINA WP2.2A (e.g. Becker *et al.*, 2008).

Calculation of risk performance measures

The probability or likelihood of occurrence of a scenario is needed in order to calculate risk performance measures (the likelihood of occurrence of a scenario multiplied by the severity of its consequences). In some regulatory regimes, dose criteria differ for likely and less probable (altered evolution) scenarios. In the US, scenarios with a probability of occurrence of $<10^{-8}$/year do not need to be considered further (Section 2.2.1). A qualitative estimate of probability (such as likely/unlikely/very unlikely/impossible to occur) may be used to categorise and classify scenarios, where it is not possible or desirable to calculate probabilities numerically.

As noted above, it is difficult to quantify scenario probabilities, and hence calculate risk, except where the uncertainties associated with the scenario-forming FEPs are aleatory (random) in nature or where there is sufficient geological or historical data to estimate probability. Even if quantification of scenario probabilities is not justifiable, some judgement of the relative likelihood of aleatory FEPs is usually possible. It is more difficult to assign probabilities to scenarios based on epistemic (knowledge-based) uncertainties, such as the presence of an unidentified feature or future glaciation.

2.2 Estimation of Scenario Probabilities: Examples of Application in PA

Section 2.1 describes approaches used for the estimation of FEP and scenario probabilities. This section – and Section 3 - provide examples from selected national programmes to illustrate different approaches:

- Section 2.2.1 – The TSPA for the US Yucca Mountain Project (US DOE, 1998) provides an example of a full probabilistic assessment, which combines a probabilistic consequence analysis with the probability of occurrence of the scenario (a similar methodology was used in the WIPP project).
- Section 2.2.2 – The Nagra (2002) PA provides an example of a mainly deterministic approach, in which the probability of occurrence of the event may be qualitatively assessed (i.e., categorised but not quantified) and combined with a deterministic consequence assessment.
- Section 3 - VTT presents examples from Sweden and Finland of partial probabilistic approaches to evaluation of scenario uncertainty.

Additional information on the US and Swedish approaches is contained in the PAMINA Milestone M2.2.E.5 (Röhlig and Plischke, 2009); this report also contains information on the fully probabilistic approach to assessing uncertainty – including scenario uncertainty - in a 1992 PA conducted by the UK regulator (Dry Run 3).

2.2.1 Yucca Mountain, United States

The US Department of Energy (US DOE) Yucca Mountain Project produced a TSPA for the 2008 Licence Application for a proposed geological disposal facility for spent fuel and high-level defence waste at Yucca Mountain, Nevada (US DOE, 2008). Due to regulatory requirements, the TSPA implemented a fully probabilistic risk analysis through a five-step process conducted through an iterative process over many years:

1. Development and screening of scenarios based on FEPs.

2. Development of computational models for each scenario that encompass the relevant FEPs, using a combination of established equations and empirical data.
3. Estimation of parameter ranges, including the associated variability and uncertainty arising from, for example, heterogeneity of the geosphere or lack of complete knowledge of the site and processes that will occur in the future.
4. Calculation of consequences using Monte Carlo analysis to sample from the PDFs developed in the third step. This ensures that the uncertainty and variability associated with the parameters are included in the results.
5. Summation of probability-weighted dose rates over all scenarios, and comparison of calculated dose rates with regulatory limits and interpretation of results.

In the first step, a review of international programmes and Yucca Mountain Project literature was used to identify more than 1,000 FEPs. FEPs were screened out of the TSPA if sufficiently unlikely or if the consequences of the FEPs were unimportant in comparison with regulatory dose limits. The probability screening threshold, as stated by the US Environmental Protection Agency (US EPA), was any FEP estimated to have a less than one chance in 100,000,000 per year of occurring (40 CFR Part 197; US EPA, 2008).

The probabilistic TSPA combines the probability of a scenario occurring with the consequences of that scenario to estimate risk. The principle of *maximum entropy* was used as a guide to select a probability model consistent with available data, while maintaining the broadest range of uncertainty appropriate for the FEP. Uncertainty in the risk estimates also arises from uncertainty in FEP characteristics, and is quantified using PDFs to represent each parameter.

One primary regulatory performance measure for Yucca Mountain is a mean dose limit to an individual, based on probabilistic analysis (US EPA, 2008). The TSPA quantitatively estimated mean dose to respond to this quantitative regulatory criterion by aggregating virtually all of the FEPs into a system model applied to the following scenarios:

- Nominal Scenario Class
  - Nominal Modelling Case (combined with Seismic Ground Motion for million-year analyses)
- Early Failure Scenario Class
  - Waste Package Modelling Case
  - Drip Shield Modelling Case
- Igneous Scenario Class
  - Intrusion Modelling Case
  - Eruption Modelling Case
- Seismic Scenario Class
  - Ground Motion Modelling Case

- Fault Displacement Modelling Case

As an example, one potentially disruptive event considered was volcanic eruption (Figure 2.2; US DOE, 2008; Crowe *et al.*, 2006). The risk of volcanism has two components, namely the probability that a volcanic eruption will occur in the Yucca Mountain region during the life span of the disposal system, and the effect of an eruption on the performance of the system.

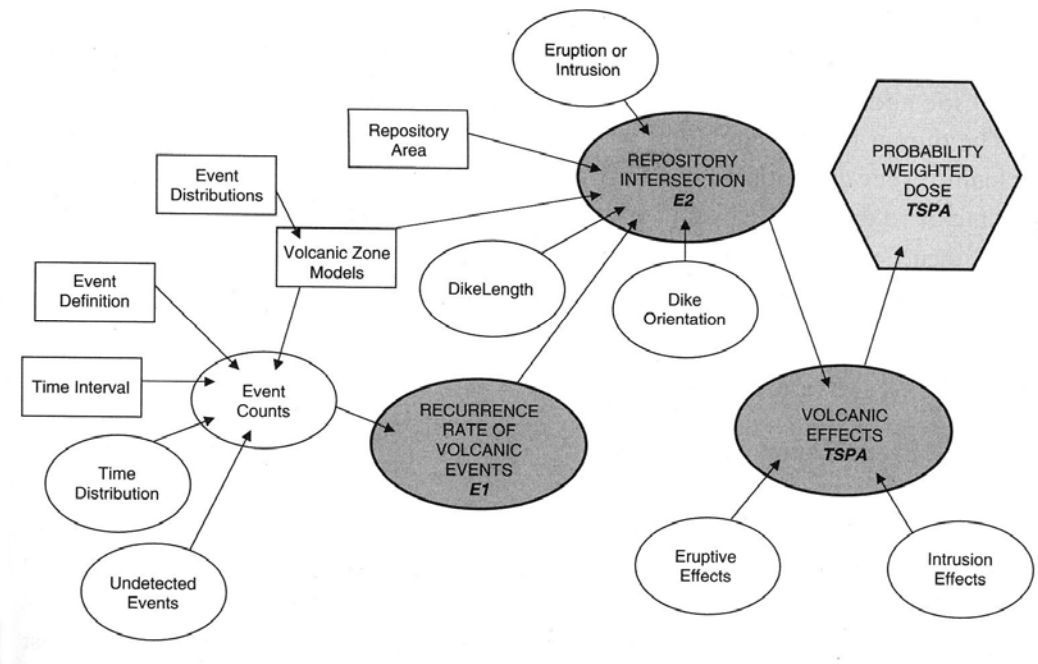

Figure 2.2: Logic diagram for the Yucca Mountain volcanism decision problem (Crowe *et al.*, 2006). E1 and E2 are defined in the text.

The probability of occurrence of a volcanic event that disrupts the repository system is:

$$Pr_d = Pr(E2 \text{ given } E1) \cdot Pr(E1),$$

where E1 is the likelihood of occurrence of a future eruptive or intrusive event in a volcanic zone and E2 is the likelihood of an event occurring within a volcanic zone that also intersects the repository.

In order to estimate the probability and consequences of such an event, the following information is required:

- A model for the definition and number of volcanic events that may occur within each zone.
- The spatial, structural or conceptual models of zones where a volcanic event may occur.
- The distribution and properties of volcanic events in these zones.
- The location and area of a geological disposal facility.

- The radiological release and dose associated with a volcanic disruption.

A simulation model combines assumptions and parameters (described using PDFs to represent uncertainty) to estimate E1 and E2, and so calculate Pr_d. Similar approaches are taken for each scenario to obtain scenario probabilities.

The scenario probability is applied as a weighting factor to the radiological dose calculations performed for each scenario. The probability-weighted consequences of each scenario are averaged over the aleatory uncertainty represented by each scenario, and the resulting expected dose values (expectation over aleatory uncertainty) are summed over all scenarios. Uncertainty in the expected dose arises from epistemic uncertainty in parameter values (i.e. FEP characteristics); thus, the computation is repeated for a number of sampled values from the PDFs that characterise FEP uncertainty. Finally, the mean dose (expectation over epistemic uncertainty) is compared with the regulatory dose constraints, as illustrated in Figure 2.3.

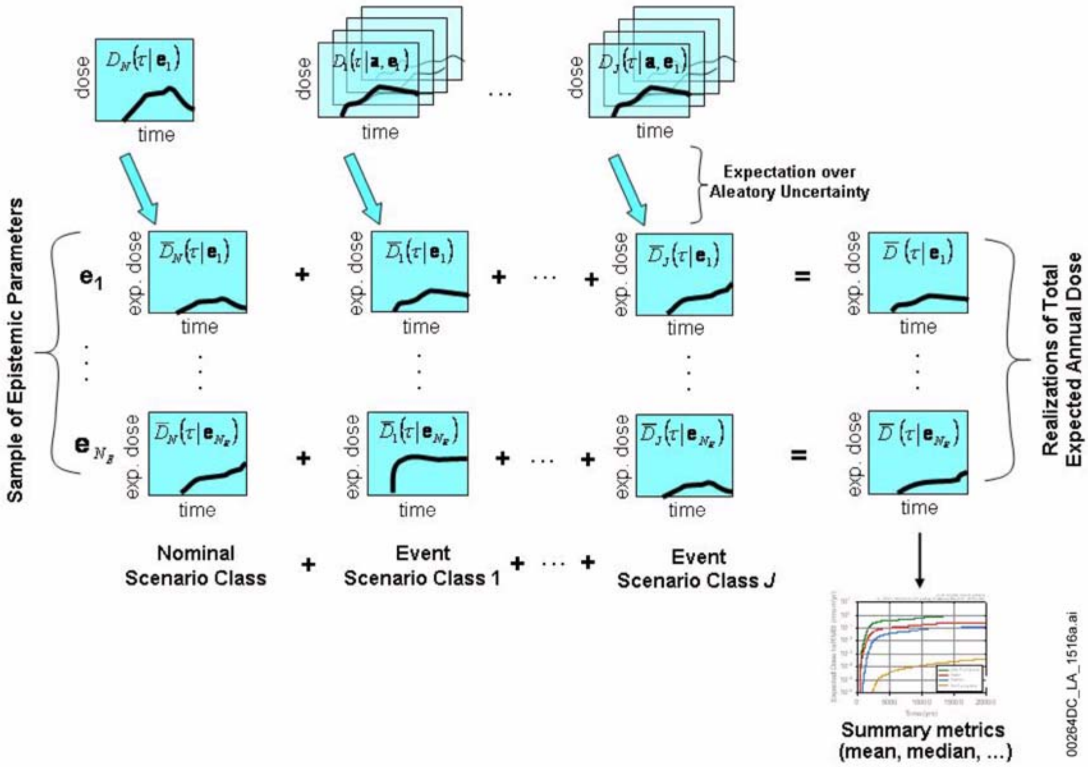

Figure 2.3: Yucca Mountain TSPA methodology for the 2008 Licence Application, illustrating the computational strategy for total expected annual dose (expectation over aleatory uncertainty) as a sum of expected annual doses for each event scenario class (or each modelling case) (from US DOE, 2008). Epistemic uncertainty is associated with the values of parameters used in consequence modelling. Note: $D(\tau,\mathbf{e}_i)$ = total expected annual dose at time t, for epistemic sample $\mathbf{e}_i$. $D_J(\tau,\mathbf{a},\mathbf{e}_i)$ = annual dose for event scenario class J (or modelling case J), for epistemic sample $\mathbf{e}_i$ and aleatory vector $\mathbf{a}$.

2.2.2 Nagra, Switzerland

The PA for the disposal of spent fuel, vitrified high-level waste (HLW) and long-lived intermediate-level waste (LL-ILW) in the Opalinus Clay of the Zürcher Weinland in Switzerland (Nagra, 2002) used an approach in which scenarios with different probabilities are treated in different ways. Each assessment case was based on a scenario that determines the main pathway of radionuclide release. Assessment cases were defined that:

- Address the release of radionuclides dissolved in groundwater through a system of homogeneous clay barriers of very low permeability, assuming that the system evolves broadly as expected (the Reference Scenario), exploring the range of possibilities arising from particular uncertainties affecting the barrier system where this range can be bounded with reasonable confidence on the basis of available scientific understanding.
- Explore the consequences of the release of radionuclides as volatile species in the gas phase.
- Look at different (stylised) possibilities for the release of radionuclides affected by human actions.
- Test the robustness of the barrier system ("what if" cases).
- Consider design / system options.
- Deal with different (stylised) possibilities for the characteristics and evolution of the surface environment (the biosphere).

The Reference Case, based on the Reference Conceptualisation of the Reference Scenario (Figure 2.4), envisages "*a repository with a near field evolving according to the design functions of the engineered barriers, a geosphere based on the current understanding of the geological environment and a biosphere based on present-day geomorphological, hydrogeological and climatic conditions, with conservative assumptions regarding human behaviour and diet*" (Nagra, 2002).

The effects of uncertainties on the future evolution of the system are explored using alternative scenarios, which are identified using expert judgement, based on an understanding of the system evolution and the fate of radionuclides in the Reference Case. For a given scenario, different conceptualisations are considered, such as alternative phenomena in the near field and the geosphere, where uncertainty exists about their importance for the reference radionuclide release pathway. Parameter value uncertainty within alternative conceptualisations is investigated by parameter variations (Figure 2.4).

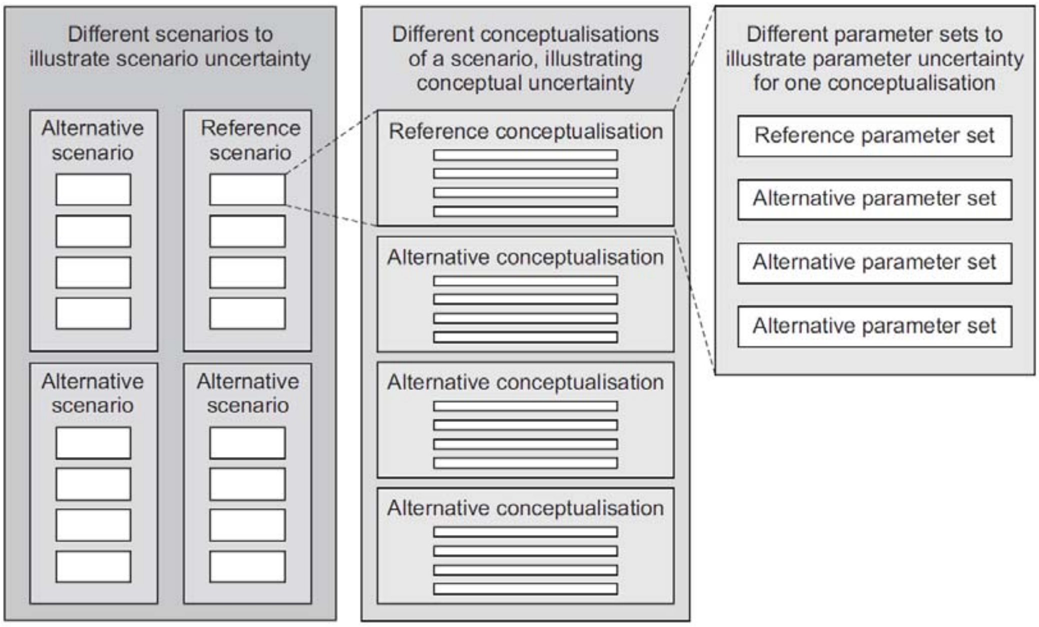

Figure 2.4: The approach to uncertainty assessment in Switzerland (Nagra, 2002). Each assessment case is defined in terms of a scenario, a number of conceptual assumptions for modelling key FEPs, and a range of alternative parameter sets.

The main aim within the PA was to comprehensively identify sources of uncertainty. However, excessive demands were not placed on the level of detail for quantifying uncertainties, including scenario probabilities: "*for those uncertainties that are difficult to quantify with respect to their likelihood of occurrence, bounding assessments are considered to be acceptable*" (Nagra, 2002). Consistent with this, the Reference Case (expected evolution scenario) is given a probability of one, and variant scenarios are also conservatively given a nominal probability of one for the purposes of comparison with the Reference Case. This approach has the advantage of not placing undue emphasis on calculations of scenario probability that contain significant uncertainty.

In general, uncertainties were evaluated in terms of their potential relevance to safety. On the basis of this evaluation, the consequences of some uncertainties are "*judged to be very small, or irrelevant to safety, or the likelihood of occurrence or degree of belief of some potentially perturbing events and processes is judged to be negligible*" (Nagra, 2002). These uncertainties were considered in "what if" cases to test the robustness of the repository system by exploring scenarios where key safety functions are perturbed. These cases illustrate the behaviour of the disposal system under extreme conditions that are outside the range of possibilities supported by scientific evidence.

Note that new work by Nagra in PAMINA WP2.2.E is aimed at developing a TSPA approach to the treatment of uncertainty, including the consideration of scenario uncertainty.

2.3 Estimation of Scenario Probabilities: Regulatory Perspective

The approaches to estimating scenario probabilities differ between regulators; more specifically, different regulatory approaches have been adopted in Europe and the US. In this context, the approaches by the UK environment agencies (Section 2.3.1), a European Pilot Study on the "Regulatory Review of a Safety Case for Geological Disposal of Radioactive Waste" (Section 2.3.2), and the US Environmental Protection Agency (EPA) regulations for the WIPP (Section 2.3.3) are described.

2.3.1 UK Environment Agencies' Guidance on Requirements for Authorisation (GRA)

In recently updated guidance applicable to geological disposal facilities in the UK (the GRA), the environment agencies provide guidance on the approaches to risk assessment and the treatment of uncertainties (Environment Agency and NIEA, 2009). Uncertainties are classified according to whether they can be reliably quantified. Uncertainties that cannot be reliably quantified include those for which it is not possible to acquire relevant data, or acquiring enough data to evaluate the uncertainty statistically could only be done at disproportionate cost. For example, any historical data for a rare event such as a "*severe earthquake at a specific location in a region of generally low seismicity*" would likely not provide an adequate basis for statistical evaluation.

The environment agencies expect that uncertainties that can be reliably quantified will be considered within a numerical risk assessment developed as part of an environmental safety case.

Unquantifiable uncertainties must also be addressed within the environmental safety case but should be given separate consideration. One approach (Figure 2.5) is to use these uncertainties to define scenarios (e.g., altered evolution and bounding scenarios) and to undertake conditional risk calculations (i.e., to assign a nominal probability of one to each scenario). Results can be qualitatively compared with the risk guidance level (a radiological risk of 10^{-6}/year to a person representative of those at greatest risk). Because these results are conditional risks, the qualitative comparison should also consider the likelihood that "*the assumptions made in setting up the scenario would correspond to circumstances arising in practice*" (Environment Agency and NIEA, 2009). Because this likelihood is unquantifiable, this comparison will necessarily involve judgement, and it is important that the information provided on this type of uncertainty is sufficiently detailed to support these judgements.

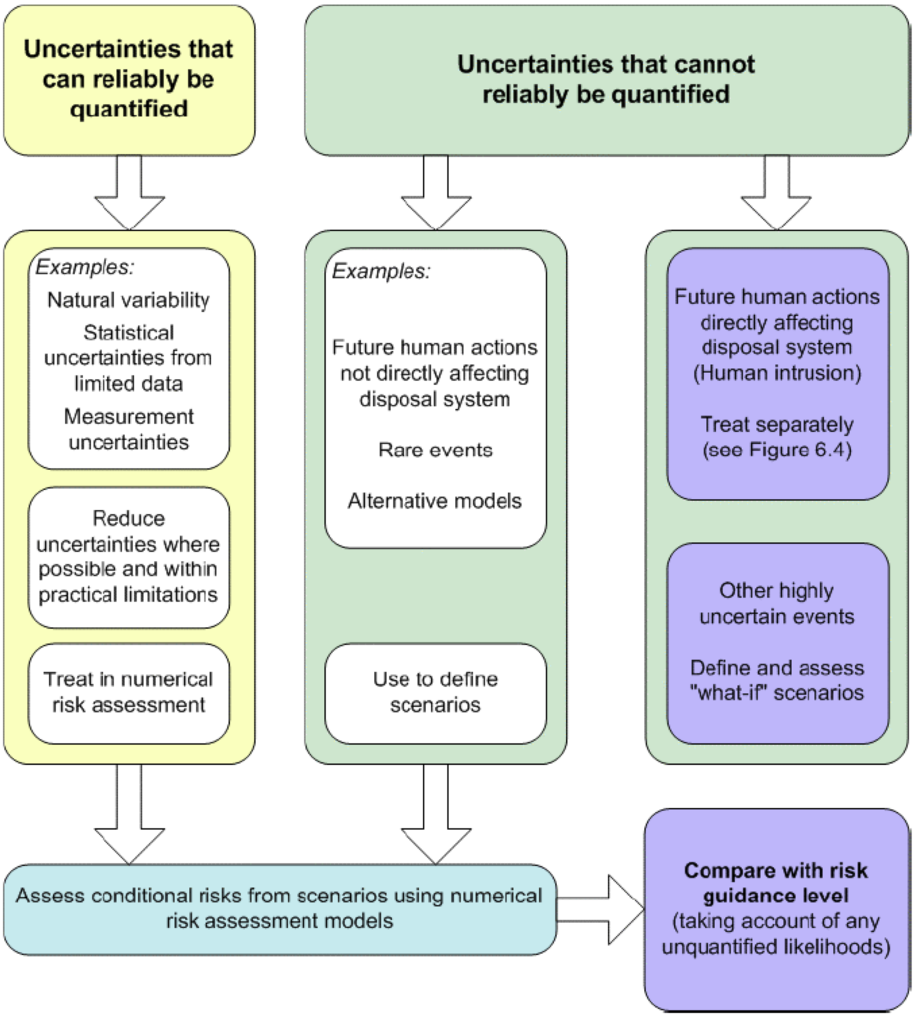

Figure 2.5: UK regulatory guidance on the treatment of uncertainties (from Environment Agency and NIEA, 2009).

In addition to unquantifiable uncertainties considered through conditional risk calculations, the GRA recognises another class of unquantifiable uncertainties relating to highly uncertain events ("what if" scenarios) or future human actions that directly affect the disposal system. For these, "… i*t may not be appropriate to undertake numerical risk assessments for comparison with the risk guidance level, as this could distort the overall picture of risks*" (Environment Agency and NIEA, 2009).

The GRA directs the developer/operator of a geological disposal facility to assume that future human actions directly affecting the disposal system are highly unlikely to occur. The UK environment agencies' approach to human intrusion is summarised in PAMINA report M3.1.12 (Morris *et al.*, 2009). Briefly, a stylised approach is likely to be used to treat human intrusion because of the inherent uncertainty in trying to predict what people might do in the future. 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). A stylised human intrusion scenario is also specified by the US regulator for

Yucca Mountain (at 10 CFR Part 63.322). Such approaches are 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 PA for comparison with dose or risk constraints. Instead, the consequences of one or more stylised scenarios should be considered to evaluate the resilience of the disposal system design to such events (ICRP, 1998).

2.3.2 European Pilot Study

A European Pilot Study on the "Regulatory Review of a Safety Case for Geological Disposal of Radioactive Waste" was conducted by the following regulators or technical support organisations from 2005 to 2007 (Lacoste, 2007):

- HSK (Swiss Nuclear Safety Inspectorate), Switzerland.
- FANC (Federal Nuclear Control Agency), Belgium.
- AVN[1] (Nuclear Safety Institute), technical support organisation to Belgian regulators.
- ASN (Nuclear Safety Authority), France.
- GRS (Company for Reactor Safety), technical support organisation to the German regulators.
- Environment Agency, UK.
- CSN (Spanish Nuclear Safety Council), Spain.
- SSI[2] (Swedish Radiation Protection Institute), Sweden.

A subproject on the treatment of uncertainty in a safety case discussed issues associated with scenario development and the modelling of scenario consequences (Vigfusson *et al*., 2007). The study noted that the TSPA approach can be used to derive the most likely outcome of a scenario, together with an assessment of uncertainty. One advantage of the TSPA approach is that all quantifiable uncertainties are treated within a uniform, systematic and logical framework, which strengthens the understanding of the overall behaviour of the system.

The study discussed several issues that need to be considered in undertaking the results of an approach that attempts to build all scenarios into a single TSPA:

- Scenario development is still required even where all scenarios are explicitly built into a TSPA model.

[1] Responsibility for regulatory support now transferred to a new organisation, BEL V.

[2] Now under a new body, the Swedish Radiation Safety Authority, SSM.

- Probabilities of occurrence need to be generated for every FEP considered, including those that cannot be readily quantified.
- Very many simulations may be required to ensure adequate exploration of probability space, particularly for low-probability FEPs.
- There may be difficulty in incorporating additional FEPs into the analysis or exploring the potential impacts of scenarios in different ways, without re-running the whole assessment.

The study also discussed an important presentational issue associated with the TSPA approach: the presentation of TSPA results in an aggregated manner for comparison with numerical standards or criteria may be difficult to understand, and must be supported by disaggregated assessment outputs. Disaggregation of results into key strands can be used to test the strength of the safety case and to explore the treatment of uncertainties and the reasons for any non-compliant single simulations. Disaggregation may also be used to identify bounding cases, for which deterministic assessments can be carried out.

Dialogue on the safety case between the developer, regulators and stakeholders will need to be at various levels of disaggregation to provide the necessary confidence in the results.

The regulators involved in the study concluded that scenario uncertainty should be dealt with by:

- Capturing uncertainties effectively and efficiently in a technical sense, by whatever means is deemed best for any given uncertainty.
- Capturing uncertainties effectively and efficiently in a presentational sense.
- Minimising the number of different scenarios to be considered quantitatively.[3]

Quantitative assessments of scenarios may be wholly deterministic or may seek to capture a range of uncertainties using probabilistic methods. A safety case will, in general, benefit from including both probabilistic and deterministic assessments.

2.3.3 US EPA WIPP (40 CFR Part 194)

The WIPP is located in southeastern New Mexico, 26 miles southeast of Carlsbad. It is operated by the US Department of Energy (DOE) for the disposal of transuranic (TRU) waste and is certified by the US EPA through 40 CFR Part 191 (disposal regulations; US EPA, 1985) and 40 CFR Part 194 (criteria for certification and re-certification of compliance with 40 CFR Part 191; US EPA, 1996). The current status of the re-certification process is described by US EPA (2009)

[3] Scenario subsumption provides ones means to reduce the number of scenarios requiring detailed quantitative analysis – see Section 2.1.2.

The 40 CFR Part 194 regulations specify that the DOE shall document the effects of potential changes in hydrogeological, geological (e.g. dissolution, near-surface geomorphology, related subsidence) and climatic (e.g. increased precipitation) processes, assuming that future characteristics that are unrelated to hydrogeological, geological or climatic conditions remain constant.

PAs are required to "*consider natural processes and events, mining, deep drilling and shallow drilling that may affect the disposal system during the regulatory time frame*" (US EPA, 1996). The 40 CFR 194 criteria are site-specific and include assumptions made by the regulator on behalf of the operator.

The US EPA specifies that mining for natural resources "*shall be assumed to occur with a one in 100 probability in each century of the regulatory time frame*" (10,000 years after disposal). It also specifies in detail the assumptions and calculation process to be used for estimating the likelihood and consequences of drilling events in a PA:

> "*Inadvertent and intermittent intrusion by drilling for resources (other than those resources provided by the waste in the disposal system or engineered barriers designed to isolate such waste) is the most severe human intrusion scenario.*
>
> *In performance assessments, drilling events shall be assumed to occur in the Delaware Basin at random intervals in time and space during the regulatory time frame.*
>
> *The frequency of deep drilling shall be calculated in the following manner:*
>
>> *(i) Identify deep drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.*
>>
>> *(ii) The total rate of deep drilling shall be the sum of the rates of deep drilling for each resource.*
>
> *The frequency of shallow drilling shall be calculated in the following manner:*
>
>> *(i) Identify shallow drilling that has occurred for each resource in the Delaware Basin over the past 100 years prior to the time at which a compliance application is prepared.*
>>
>> *(ii) The total rate of shallow drilling shall be the sum of the rates of shallow drilling for each resource.*
>>
>> *(iii) In considering the historical rate of all shallow drilling, the Department may, if justified, consider only the historical rate of shallow drilling for resources of similar type and quality to those in the controlled area.*

Performance assessments shall document that in analyzing the consequences of drilling events, the Department assumed that:

(i) Future drilling practices and technology will remain consistent with practices in the Delaware Basin at the time a compliance application is prepared. Such future drilling practices shall include, but shall not be limited to: The types and amounts of drilling fluids; borehole depths, diameters, and seals; and the fraction of such boreholes that are sealed by humans; and

(ii) Natural processes will degrade or otherwise affect the capability of boreholes to transmit fluids over the regulatory time frame.

With respect to future drilling events, performance assessments need not analyze the effects of techniques used for resource recovery subsequent to the drilling of the borehole."

For the WIPP, the regulator therefore specified the assumptions and calculation processes for the developer to use in developing and assessing stylised human intrusion scenarios. The EPA also specified that PAs do not need to consider processes and events that have less than one chance in 10,000 of occurring over 10,000 years.

2.4 Summary

Approaches for the quantification of scenario probabilities have been reviewed through an analysis of the classification of scenarios and methods for scenario development. The application of these approaches in probabilistic and deterministic PAs were also explored, and regulatory approaches to the estimation of scenario probability in Europe and the US were examined.

The identification of FEPs that could potentially affect the disposal system, and the organisation of these into different types of scenario are key steps for the quantification of scenario probabilities. In deterministic approaches to scenario uncertainty, the reference scenario includes those FEPs that are certain to occur and is normally assumed to have a probability of one. FEPs that are not certain to occur are considered through the analysis of altered evolution or other scenarios. Depending on the type and purpose of the assessment, the probability of these scenarios may be derived from the probability of the "scenario-forming" FEPs or may also be assumed to be one. In the latter case, the significance of the conditional risk or dose calculations are assessed qualitatively.

In the Swiss Opalinus Clay PA, the Reference Case (expected evolution scenario) was given a probability of one, and separate cases were developed for variant scenarios that were considered less likely. These variant scenarios were also given a nominal probability of one for the purposes of comparison with the Reference Case. This approach has the advantage of not placing undue emphasis on calculations of scenario probability that contain significant uncertainty.

In contrast, the US Yucca Mountain and WIPP projects use fully probabilistic TSPAs. In these PAs, the probability of occurrence of events was based on analysis of the frequency of previous events and expert judgement. For example, in the Yucca Mountain TSPA, the probability of occurrence of a disruptive volcanic event was calculated based on previous volcanic eruptions and assumptions of the disruption caused by such an event. Scenario probabilities were estimated by combining the probability of scenario-initiating events and subsidiary FEPs.

There are contrasting regulatory views on the estimation of scenario probability in the US and Europe:

- In Europe, developers/operators of geological disposal facilities are encouraged to develop a limited number of illustrative scenarios to enhance understanding of the disposal system and its evolution. Regulators accept both deterministic and partial probabilistic methods, 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, which is assigned a nominal probability of one. Scenarios involving highly uncertain future events and human actions should be treated separately and may be assessed qualitatively.
- In the US, the regulator is more prescriptive, specifying that developers/operators of geological disposal facilities must conduct probabilistic assessments and, in the case of WIPP for example, the assumptions to be made and the methods to be used in developing disturbed performance (mining and drilling) scenarios.

Given the large uncertainties involved, the main consideration in the assignment of probabilities to events and processes 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.

3 Scandinavian Case Studies (VTT)

Information reported in this section was compiled by VTT from safety assessments conducted in Sweden and Finland, namely SR-Can, TILA-99, RNT-2008, and safety assessments for KBS-3H:

- The KBS-3 approach, based on multiple barriers, is the proposed spent fuel disposal method both in Sweden (the candidate sites are Forsmark and Laxemar) and Finland (at Olkiluoto). KBS-3H (horizontal emplacement) and KBS-3V (vertical emplacement) are the two design alternatives of the KBS-3 method.
- The Swedish Nuclear Fuel and Waste Management Company (SKB), which is responsible for the management and disposal of all radioactive waste from Swedish nuclear power plants (NPPs), has performed several reviews of the long-term safety of a final disposal facility for spent nuclear fuel. The latest in the series is called **SR-Can** and was published in November 2006.
- The Finnish nuclear waste disposal company, Posiva, is planning an underground disposal facility for spent nuclear fuel at Olkiluoto on the south-west coast of Finland. The **TILA-99** long-term safety assessment was one of the earlier studies conducted by Posiva. It did not focus on the Olkiluoto site alone, but addressed four investigation sites.
- Posiva and SKB have conducted a joint research, demonstration and development programme in the period 2002–2007 to establish whether KBS-3H represents a feasible alternative to the reference alternative KBS-3V. The safety studies conducted as part of this programme included a safety assessment of a preliminary design of a KBS-3H repository at the Olkiluoto site (Smith *et al.*, 2008).
- The repository design for the planned underground disposal facility for spent nuclear fuel at Olkiluoto is based on the KBS-3V concept (see next bullet point and Section 3.1). Within Posiva's safety case, **RNT-2008** presents the radionuclide release and transport analysis, covering the release of radionuclides from the disposal facility to their arrival in the biosphere.

This section is structured as follows: Section 3.1 provides an outline of the KBS-3 repository concept; Section 3.2 describes and provides examples of the scenarios assessed in Swedish and Finnish safety reports, in the context of quantification of scenario probability; and Section 3.3 provides a brief summary outlining the main findings of the Scandinavian study of practices for quantifying the probabilities of scenarios.

3.1 Outline of the KBS-3 Disposal Concept

The basic concept of the Swedish KBS-3V (and KBS-3H) design for the disposal of spent nuclear fuel is based on its encapsulation and emplacement in crystalline rock at a depth of between 400 m to 700 m (Vieno and Nordman, 1999) (Figure 3.1).

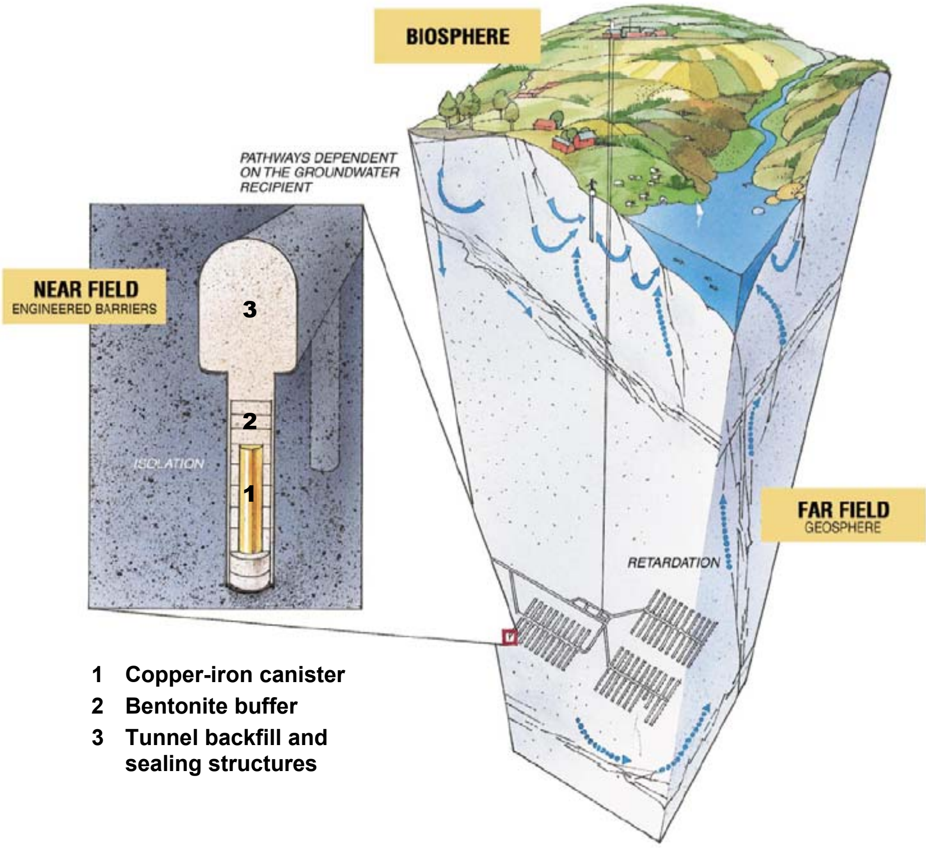

Figure 3.1: Schematic view of the KBS-3V deep disposal system, illustrating emplacement of a copper-iron canister (1) in compacted bentonite buffer (2) and sealing off the tunnels with backfill material (3) (modified after Ericsson, 1999).

The spent fuel is planned to be encapsulated in canisters with a cast iron insert and a copper overpack (50-mm nominal thickness) (Figure 3.2).

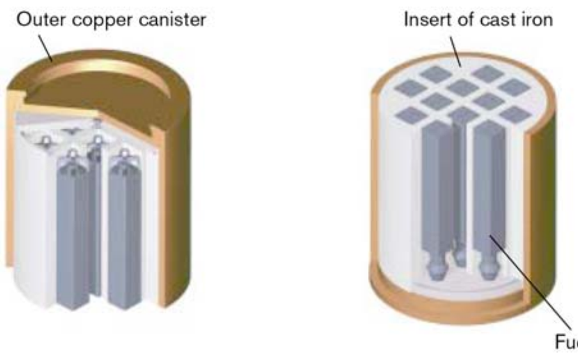

Figure 3.2: Exploded view of spent boiling water reactor (BWR) fuel disposal canister (from King *et al.,* 2002).

In the KBS-3V alternative, once filled and sealed, the copper-iron canisters will be emplaced individually in vertical boreholes in the floors of deposition tunnels feeding off central tunnels. In the KBS-3H alternative, the boreholes are horizontal and hundreds of metres long. The space between the canisters and the wall of the borehole will be filled with compacted bentonite. The tunnels and shafts of the KBS-3V alternative will be backfilled, and sealing plugs will be emplaced to block pathways for groundwater flow.

The safety of the KBS-3 concept is based on long-term isolation (>100,000 years) of radionuclides in copper-iron canisters surrounded by a buffer of compacted bentonite clay. The main function of the canisters is to isolate the spent fuel from the surrounding environment. The canister has been regarded as the most important barrier in the disposal system, such that:

- The canister overpack should provide corrosion resistance for at least 100,000 years.
- The canister insert must provide sufficient mechanical strength to withstand the loads caused by hydrostatic pressure from groundwater at the disposal depth, by the pressure from the swelling of the buffer, and by ice sheets during future glaciations.

The bentonite buffer will be of low hydraulic conductivity and high sorption capacity, and will perform the following functions in the disposal system:

- Keep the canister in place.
- Provide good chemical and mechanical stability.
- Guarantee mass transfer predominantly by diffusion to limit the transport of corrosive substances to the canister.
- Have a high capacity to deform under load and, consequently, to protect the canister from mechanical damage caused by shear movement of the host rock.
- Provide chemical (redox and pH) buffering.

The tunnel backfill to be used in the KBS-3V alternative will have a hydraulic conductivity comparable to that of the host rock, and will perform the following functions:

- Minimise the expansion of the buffer into the backfill and, hence, help keep the canister in place.
- Provide load-bearing support against the tunnel roof.
- Minimise groundwater channelling in the tunnels and surrounding Excavation Disturbed Zone (EDZ).
- Promote reducing conditions.

3.2 Types of Scenarios

A key uncertainty that must be addressed concerns comprehensiveness issues, i.e., whether all aspects important for the safety evaluation have been identified and whether these aspects are being captured, e.g., through the selection of an appropriate set of scenarios. The selection of scenarios is subjective, meaning that it is difficult to propose a transparent 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 in SR-Can (SKB, 2006), such as:

- A structured and logical approach to the scenario selection.
- The use of safety function indicators in order to focus the selection on issues relevant to safety.
- The use of bounding calculations 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.
- Quality assurance (QA) measures to ensure that all FEPs have been properly handled in the assessment.
- The use of external reviews.

In the SR-Can report, the scenarios are classified (based on the Swedish regulatory guide SKIFS 2002:1) (SKI, 2002) into three groups according to their probabilities:

- *High-probability scenarios*, which is relevant only to the main scenario of SR-Can.
- *Less likely scenarios*, which cannot be ruled out and which are included to address uncertainties that are not evaluated within the framework of the main scenario.
- *Residual scenarios*, which are selected and studied independently of probability in order to illustrate the significance of individual barriers and barrier functions. A residual scenario is not included in the risk assessment for the repository.

There is no numerical limit to the probability below which a scenario is considered as residual in SR-Can. A scenario is therefore considered to be residual if it can be argued that the scenario is not physically reasonable.

In the following analyses it must be kept in mind that in most cases the probability of a chosen scenario is a very subjective number.

3.2.1 High-Probability Scenarios

Sweden

In SR-Can it was assumed that all the canisters are intact after emplacement. Two variants of the reference evolution (base case) are discussed (SKB, 2006):

1. A variant in which the external conditions during the first 120,000 years are assumed to be similar to those experienced during the most recent glacial cycle, the Weichselian. Thereafter, seven repetitions of that cycle are assumed to cover the entire 1,000,000-year assessment period.

2. A variant in which the future climate, and hence external conditions, are assumed to be substantially influenced by anthropogenic greenhouse gas emissions. It is assumed that the climate will return to normal after the extra greenhouse gases have been removed from the climate system by natural processes. In practice, it is assumed that the temperate domain will prevail for 50,000 years more than for the base case, after which the beginning of Weichselian (70,000 years) is imposed.

The only failure mode occurring in variant [1] above is the copper overpack corroding earlier, resulting in buffer erosion, which in turn leads to advective conditions in the buffer. Uncertainties regarding this failure mode are further analysed in a copper corrosion scenario, leading to the conclusion that the consequences could be somewhat higher than in the main scenario. In SR-Can, it **was not found meaningful to assign any probability less than one** to the increased consequences, partly because these were not much higher than the consequences of the more probable cases analysed in the main scenario, and partly because many of the uncertainties involved cannot be quantified at this stage (SKB, 2006). This means that, in the final risk summation, the higher consequences for the corrosion scenario, assigned **a probability of one**, replace those for the main scenario for the same failure mode.

Finland

Although in SR-Can, no initial penetrating defects are expected (i.e., the scenario has a low probability), the evolution in case of a growing pinhole failure was described and its consequences evaluated (SKB, 2006, Section 10.5). Although there are differences in Posiva's and SKB's canister designs, including the chosen reference welding techniques, the probability of initial penetrating defects in Finnish canisters is also expected to be low. However, in Finnish safety assessments, an initial pinhole failure has always been assumed, but its probability remains to be addressed and the QA programme for non-destructive testing techniques is still in an early phase of development. **Thus, Posiva is not yet taking any position on the likelihood of occurrence of canisters with initial penetrating defects.**

In Finnish safety assessments, there are also scenarios where copper canister failure takes place, e.g. at 100,000 years. This follows from buffer erosion leading to advective conditions in the buffer. **The probability of canister failure has been set to one**, but it will be evaluated more precisely in the future (the stability of the bentonite buffer is currently being studied).

3.2.2 Less Likely Scenarios

Sweden

In SR-Can, three scenarios are considered as "less likely", namely rock shear, canister failure due to corrosion, and future human actions (SKB, 2006):

- A numerical value (**estimation of rock shear movement probability**) has been used for the rock shear case.
- **The probability that one of the 6,000 canisters fails at Forsmark during the initial 120,000-year glacial cycle is 1.4×10^{-2}. The corresponding value at**

Laxemar is 7.7×10^{-3}. In one million years, the corresponding probabilities are 1.17×10^{-1} and 6.45×10^{-2}, respectively. However, according to SKB (2006), there is no basis for assigning probabilities to the set of corrosion cases, so a **probability of one** has been used.

- A set of scenarios related to future human actions was also defined and analysed. Human intrusion scenarios resulting in a degradation of system performance are to be considered as "less likely scenarios" according to SKI[4] (Swedish Nuclear Power Inspectorate) regulations, but are not to be included in the risk summation according to SSI[4] (Swedish Radiation Protection Authority) general guidance.

Finland

In recent Finnish safety assessments, a numerical value for probability has been used for rock shear only. The expected value of the number of canisters in the KBS-3H repository that could potentially be damaged by rock shear in the event of an earthquake has been calculated to be 16 out of a total of 3000 canisters (i.e., the fraction is 0.0053 of disposed canisters). For KBS-3V, a slightly higher value of 20 is calculated, the difference being largely due to the greater vertical extent of a KBS-3V repository and hence its greater vulnerability to movement along the relatively dense population of sub-horizontal fractures. However, there are some significant uncertainties associated with these values, which could lead to an underestimate or an overestimate of the actual likelihood of damage (see Section 7.4.5, Smith *et al.* 2007). **The probability of an earthquake occurring that is sufficiently large to cause such damage in a 100,000-year timeframe has been estimated as 0.02** (Table 5.8 in La Pointe and Hermanson, 2002).

Several scenarios where canisters fail due to corrosion have been analysed, but as in the Swedish case, the **probability is set to be one**.

3.2.3 Residual Scenarios

Sweden

The residual scenarios in SR-Can are:

- Buffer advection.
- Buffer freezing.
- Buffer transformation.
- Canister failure due to isostatic load.

[4] SKI and SSI have been merged to form a new single body, the Swedish Radiation Safety Authority, SSM.

Finland

Examples of two residual scenarios in TILA-99 are as follows:

- Scenario in which it is assumed that immediately after disposal the copper/iron canister "disappears", and a high flow of saline ground water takes place.
- Scenario in which it is assumed that the fuel elements are completely degraded after 10,000 years.

In the recent safety assessment RNT-2008 (Nykyri *et al.*, 2008), the assumption that the initial defect in a canister has a diameter of 100 mm is considered as a residual scenario, since it is unlikely that a canister with such an initial penetrating defect would pass quality control.

3.3 Summary

In both Sweden and Finland, safety assessments of the KBS-3 approach are based on the classification of scenarios according to their probabilities.

One of the high-probability scenarios that is considered is canister failure that follows from advective conditions in the buffer due to erosion of the buffer. The probability of this scenario is currently set to one – however, the possibility of conditions in the bentonite buffer becoming advective is currently being studied, and it is hoped that a very low probability value can be demonstrated for this scenario.

A numerical value for the probability of a scenario is feasible for the rock shear case and, perhaps, for an initially defective canister case. Both of these are examples of "less likely" scenarios. It is also possible to estimate the probability of an earthquake occurring that would be sufficiently large to cause damage to the canisters.

"What if" type or residual scenarios have a probability of zero, but are needed/considered in order to illustrate the robustness or significance of barriers, or the overall robustness of the disposal system.

4 Czech Republic Case Study and Expert Judgement Research (NRI)

This section, produced by NRI, is a case study from the Czech Republic. It provides an outline of the development of scenarios (Section 4.1), summarises the approach to estimating the probability of the scenarios identified in the Czech programme (Section 4.2), and provides a review of expert judgement techniques to assign scenario probability (Section 4.3). The findings of, and recommendations from, the case study are summarised in Section 4.4.

4.1 Scenario Development

Regulatory background

The radioactive waste management legislation in the Czech Republic follows the recommendations of the International Atomic Energy Agency (IAEA) Safety Standards (IAEA, 1989). The main objectives of a Deep Geological Repository (DGR) for HLW are to isolate the wastes from the human environment, and to ensure the long-term radiological protection of humans and the environment. The releases from a DGR shall be less than the dose or risk upper bound apportioned by national authorities from individual dose or risk limits, taking into account all processes that may affect the performance of the facility.

According to the 1997 Czech Atomic Act and relevant regulations, all practices resulting in exposure shall maintain such a level of radiation protection that the risk to humans and to the environment is as low as reasonably achievable (ALARA), considering economic and social factors. This must be demonstrated, taking into account all physical, chemical and biological properties of the wastes, the site and all risks that may occur in the post-closure period.

The regulations assume that performance assessors will describe the behaviour of the disposal system and its components, and calculate consequences under all possible sets of events and processes that could occur in the future, that is, under all possible scenarios. Scenario development is thus an implicit regulatory requirement.

Key elements of the DGR

The systematic accumulation and assessment of scientific and technical data for DGR design, selection of the Engineered Barrier System (EBS), and safety evaluation in the Czech Republic started in 1993. The results were summarised in 1999 in a "Reference design report" – the proposed reference design consists of spent fuel waste packaged into carbon steel canisters, surrounded by bentonite bricks and located in tunnels at least 500 m under the surface in a granitic host rock.

The "Reference design report" included an initial "safety report" for the siting assessment of the DGR. One part of this "safety report" was devoted to the description of common techniques used to identify and screen scenarios. Scenario development was based primarily on the US Sandia (Cranwell *et al.*, 1990) and Swedish SKI/SKB (Eng *et al.*, 1994; Chapman *et al.*, 1995) approaches. These approaches were used to identify the potentially significant scenarios for the Czech DGR reference design.

The following elements, which seemed to be the most important at that time for a DGR concept in granite host rock, were defined:

- Engineered Barrier System (waste form, container, buffer, backfill, seals)
- Host rock [groundwater (chemistry), fractures (flux), mechanical stress (tectonic changes)]
- Technology (selected disposal and excavation technologies, layout of the repository, construction materials)

Specialists from different fields were asked to prepare a literature review and to classify and discuss interactions between these elements. However, the specialists focused primarily on discussing and evaluating the interactions pertinent to their fields, which introduced bias in the results. This approach was therefore abandoned.

Scenarios for the DGR

Scenario development in later years was influenced by participation of Czech experts in the NEA Performance Assessment Advisory Group (PAAG) and relevant NEA publications (NEA, 1992). The following scenarios were considered:

- Normal evolution scenario covering all processes with a high probability of occurrence.
- Altered scenarios initiated by unfavourable initial conditions:
    - Premature container defect at manufacture – can lead to earlier contact of water with waste. Calculations are the same as in the normal evolution scenario, but with other parameter values, depending on the assumed number of containers with a premature defect.
    - Damaged backfill – can lead to increased hydraulic conductivity and possible movement of container in a borehole. Calculations are the same as in normal evolution scenario, but with other parameter values for buffer and backfill, and other distances between containers and host rock.
    - Wrong container emplacement – can lead to contact of container with larger amounts of water, higher corrosion rates and higher radionuclide release rates than in the normal evolution scenario. Calculations are the same as in the normal evolution scenario, but with other distances between containers and host rock.
    - Stray construction materials left in the disposal facility – can lead to change of chemistry and properties of engineered barriers and higher corrosion rates than in the normal evolution scenario. Calculations are the same as in the normal evolution scenario, but with other values for parameters such as container lifetime and porewater composition.

  - Presence of higher amount of microbes than in the normal evolution scenario. Calculations are the same as in the normal evolution scenario, but with other values for parameters such as container lifetime and porewater composition.
  - Host rock affected by construction and operation activities – can lead to changes of stress in disposal sites or generation of fractures. Calculations are the same as in the normal evolution scenario, but with possibly changed parameter values.
- Altered scenarios initiated by climatic changes:
  - Glaciation – can lead to change of water fluxes and chemistry. The impact depends on the time of glaciation. Calculations are the same as for the normal evolution scenario, but with other values for parameters such as container lifetime and porewater composition. In the Czech Republic, the changes connected with glaciation will not be significant.
  - Permafrost formation - can lead to change of water fluxes and chemistry. The impact depends on the time of permafrost formation. Calculations are the same as for the normal evolution scenario, but with other values for parameters such as container lifetime and porewater composition. No permafrost is expected in the Czech Republic.
  - Seismic changes due to climatic changes, e.g. seismic changes after glaciation.
  - Global warming and other less significant climatic changes – only expected to lead to small changes in the host rock and the disposal facility. The major impact will be on biosphere conversion factors.
- Human induced scenarios:
  - Drilling of a borehole into the disposal facility, leading to a change of hydraulic conditions in the system and possibly a preferential pathway for radionuclide release. Calculations are the same as for the normal evolution scenario, but with other values for parameters such as container lifetime, porewater composition, and groundwater flux, depending on when the drilling occurs. The probability of this scenario is presumably very low and must be discussed.
  - Drilling through disposal units and taking samples on the surface. This is considered as a special scenario requiring another type of calculation based on exposure of workers who perform drilling and analyses. The probability of this scenario will presumably be very low.
  - Excavation work on surface – can lead to major changes in groundwater fluxes. Calculations are the same as for the normal evolution scenario, but with other parameter values.
  - Change of chemistry of the site due to human action (e.g. dumping of waste near surface, intensive agriculture). Calculations are the same as for the normal evolution scenario, but with other parameter values.

4.2 Consideration of Scenario Probability

An informal expert judgement approach was used to estimate the probability of the scenarios listed above. The methodology was scenario-dependent and was connected with the estimation of the probability of initiating events or processes taken from the NEA FEPs database (NEA, 2000).

4.2.1 Probability of Initial Unfavourable Conditions in the Repository

Since a DGR for spent fuel assemblies and HLW is considered as a nuclear facility, a DGR and its components will be subject to NPP requirements. The presence of a QA / Quality Control (QC) system will ensure that the probability of initial failure of safety-important components should be lower than 10^{-5}/year.

The components in a DGR are not exposed to changing conditions as is the case in NPPs. It can be assumed, therefore, that the probability of failure of DGR components (canister, buffer backfill, seals) due to some hidden defect will be lower than the probabilities of failure of NPP components, especially in the first hundreds of years after closure of the DGR. For example, if it is conservatively assumed that the probability of canister failure owing to initial defect is 10^{-6}/year in a DGR with 5,000 canisters, then it can be estimated that after 200 hundred years only one canister would fail due to some hidden defect.

However, this approach is difficult to apply over the whole lifetime of DGR components. Small defects can occur in some components after very long times due to exposure to unfavourable conditions. This can be important, e.g., for copper canisters, where the design lifetime can be as long as one million years, so that even failure after 10,000 years can affect repository performance. On the other hand, for carbon-steel canisters, for which the design lifetime is usually not more than about several thousands of years, premature failure of some canisters after hundreds of years cannot significantly affect disposal system performance. In fact, in PAs of a DGR with carbon-steel canisters, some distribution of the failure of canisters is always considered, and the broader the distribution of canister failures, the better the PA results.

No effect of hidden initial defects has been considered in the Czech DGR programme so far.

4.2.2 Probability of Unfavourable Naturally-Occurring Events

The probability of naturally-occurring disruptive events is minimised by the following *exclusion criteria* (SUJB, 1997):

- The occurrence of karstic phenomena to the extent of endangering the stability of the bedrock or the overlying rock cover of the land selected for siting.
- Any manifestation of post-volcanic activity, such as the escape of gases, or the occurrence of thermal or mineralised waters, found on the land of the proposed site or in its vicinity.

- Achievement or exceeding of the value of intensity of the maximum calculated earthquake 8 °MSK (scale of Medvedev-Sponheuer-Karnik for estimation of the macroseismic effects of earthquakes) on the land of the proposed site.
- The occurrence of capable and seismogenic faults with recent surface deformation and with the possibility of secondary faults, found by geological survey on the land of the proposed site.

It was considered in the first preliminary safety case that the probability of occurrence of natural events that could significantly affect performance of a DGR in the Czech Republic is negligible.

4.2.3 Probability of Human-Induced Scenarios

The probability of future human activities on the site of a DGR is reduced by the following *exclusion criteria* (SUJB, 1997):

- The existence of a significant underground water supply or mineral waters in the site vicinity.
- The occurrence of minable raw materials in the site vicinity.

No attempt has been made to quantify the probabilities of human-induced scenarios in the Czech DGR programme.

4.3 Review of Expert Judgement Techniques to Assign Scenario Probability

The basic principle underlying the methodology for estimating scenario probabilities is that it is desirable to use all available information (e.g. Hunter and Mann, 1989). There are three main sources of information: historical data, models, and expert judgement. Both historical data and models require, however, expert interpretation to estimate event probability. The problem with estimation of scenario probability is that the probability of the initiating event and the conditional probability of each subsidiary event must be known. Another problem with quantifying scenario probability is that the spectrum of possible evolutions of a repository is wide and cannot be captured in a detailed sense (Goodes *et al.*, 1991). Therefore, approaches for quantifying the probability of scenarios for gradually evolving systems and for systems affected by low-probability events are different (Mohanty and Codell, 2004). For a gradually evolving system with slow degradation of barriers, it is usually considered that each scenario that differs only in the values used for particular model parameters has an equal probability of occurrence. Expert judgement techniques are used mainly for estimating the probability of scenarios initiated by rare events.

Scientists, engineers, and managers in practically all DGR development programmes often use informal expert judgement to estimate the probabilities of rare events. The reason for using expert judgement is that assigning probabilities to some scenarios can only be based on limited data. According to Bonano and Baca (1995), whether or not expert judgement will be used is not an issue because the nature of the problem does not seem to allow for any other means to be applied. Rather, the issue is whether expert judgement will be obtained and used with a formal, semi-formal or *ad hoc* approach. The main problem with informal approaches is that it can be difficult to provide transparency of the reasoning by which experts come to their opinions and quantify them. It is difficult to directly use qualitative information in a PA, for example: "*In the case of faults that are controlling faults in low seismicity areas, the likelihood of fault rupture is probably rather low*" (Musson, 2004). Therefore, since the end of the 1980s, several approaches were developed to formalise the expert judgement process (expert elicitation), including estimation of the probability of scenarios (e.g. Hunter and Mann, 1989; Bonano and Apostolakis, 1991; Trauth *et al.*, 1994; Kotra *et al.*, 1996; Hora and Jensen, 2002; Freeze, 2005).

4.3.1 Expert Elicitation to Formalise the Expert Judgement Process

Formal expert judgement elicitation procedures were probably first in the US DGR programmes for the WIPP (Hora *et al.*, 1991; Trauth *et al.*, 1993, 1994), and for estimation of scenario probabilities for Yucca Mountain (e.g. Bonano and Apostolakis, 1991). The first formal expert elicitation panel (Hora *et al.*, 1991), related to estimation of scenario probability, was convened to identify possible modes of human intrusion over 10,000 years at the WIPP, and to estimate frequencies of such intrusions. The second panel (Trauth *et al.*, 1993) was convened to address the need for permanent, passive markers to communicate the location and nature of the wastes proposed to be disposed of in the WIPP. Frequencies of human intrusion are directly used in estimating the probability of human intrusion scenarios. The mathematical approach for calculation of scenario probability was described comprehensively, e.g., in the report of Tierney (1991). Markers can be connected indirectly with probabilities of human intrusion scenarios. The efficiency of the markers in deterring inadvertent human intrusion was estimated to decrease with time, with the probability function varying with the mode of intrusion (who is intruding and for what purpose) and the level of technological development of society.

Another expert elicitation exercise was conducted to estimate probabilities of an inadvertent human intrusion at the Nevada Test Sites Area 3 and Area 5. An expert panel, comprised of ten disciplines ranging from the social sciences to engineering and drilling, was convened to assess the site-specific probability of inadvertent human intrusion. It was found that if management controls (including markers and sub-surface barriers) are designed and implemented effectively, then the probability of inadvertent intrusion would be reduced by about a factor of ten (Black *et al.*, 1997).

4.3.2 Key Steps in Expert Elicitation

The problems with expert judgement procedures were recognised by the US Nuclear Regulatory Commission (NRC), which issued an NRC Branch Technical Position (BTP) for expert elicitation for the HLW programme (Kotra *et al.*, 1996). It recommended that a formal elicitation procedure should contain the following steps:

1. Selecting and defining technical issues (definition of objectives).
2. Selecting experts.

3. Refinement of issues and problem decomposition.
4. Assembly and dissemination of basic information.
5. Pre-elicitation training.
6. Elicitation of judgements.
7. Post-elicitation feedback.
8. Aggregation of judgements (including treatment of disparate views).
9. Documentation.

These steps are discussed in more detail below.

Step 1: Defining objectives

The first step is one of the most important. Proper definition of the objectives calls for understanding of how judgements will be used in subsequent analyses. This understanding should direct the overall content of the elicitation.

Step 2: Selecting experts

The selection of experts in the second step can also represent a type of elicitation. Before selection of the subject-matter experts, whose judgement will be elicited, the normative expert, i.e., the expert who is trained in probability theory, psychology, and decision analysis, and the generalist, who has solid general understanding of the problem, should be recruited. These two experts, together with staff of the funding organisation, form the elicitation team and participate in selecting subject-matter experts. As stated in the BTP, the panel of experts selected for elicitation should comprise individuals who:

- Possess the necessary knowledge and expertise.
- Have demonstrated their ability to apply their knowledge and expertise.
- Represent a broad diversity of independent opinion and approaches for addressing the topic.
- Are willing to be identified publicly with their judgements.
- Are willing to identify, for the record, any potential conflicts of interest.

Step 3: Refinement of issues and problem decomposition

In the third step, subject-matter experts can help the elicitation team to decompose the issue defined in step 1 into concise and distinct questions.

Step 4: Assembly and dissemination of basic information

An important part of the elicitation process is providing basic information to subject-matter experts. The elicitation team must therefore assemble a preliminary body of basic information. The elicitation team must be careful, however, not to provide information that could negatively influence the subject-matter experts. Biasing may be introduced at this influential point, and credibility of the elicitation could be reduced.

Step 5: Pre-elicitation training

The next step is pre-elicitation training. This training should:

- Familiarise the subject-matter experts with the elicitation process.
- Educate the subject-matter experts in uncertainty encoding and the expression of their judgements using subjective probability.
- Provide the subject-matter experts practice in formally articulating their judgements, as well as explicitly identifying their associated assumptions and rationale.
- Educate the subject-matter experts with regard to possible biases that could be present and influence their judgements.

There are two classes of bias: motivational and cognitive. Motivational biases occur because a subject–matter expert has a vested interest in an issue and consciously or unconsciously distorts his/her judgement. Cognitive biases occur because of a failure to process, aggregate, or integrate the available data and information.

Step 6: Elicitation of judgements

The actual elicitation of judgements must be tailored, e.g., to the specific question or issue, the type of judgement required, the resources available for the elicitation, and the availability of subject-matter experts. Reviewers should be able to discern not only the judgements themselves, but also the reasons, assumptions, approaches, and information that each of the subject-matter experts used.

Step 7: Post-elicitation feedback

After the elicitation step, the subject-matter experts should be given feedback from the elicitation team on the results as soon as practical after the elicitation sessions are completed. This step allows elicitation team members the opportunity to verify data codification and check for encoding errors.

Step 8: Aggregation of judgements

In the preceding steps, the elicitation team focused on individual judgements. To process differing judgements from multiple subject-matter experts, it may be necessary to combine the individual judgements. Two general approaches to combining expert judgements are commonly identified: behavioural aggregation and mechanical aggregation. Behavioural aggregation usually entails bringing together the subject matter experts to discuss and combine their judgements. In mechanical aggregation, individual judgements are combined mathematically such that the sum of the weighted individual judgements is normalised. These two approaches may be blended. Mathematical models are shown to experts and they are asked if they wish to revise their judgements. Various approaches of aggregating expert judgements are given in the paper of Clemen and Winkler (1999).

One of the problems of expert elicitation techniques is the consistency of expert estimations of probabilities. In the case of estimation of probabilities of mutually exclusive and exhaustive events or scenarios, the Analytical Hierarchy Process (AHP) proposed by Saaty (1980), which has been devised as a mathematical technique to analyse complex situations and assist in decision-making, can be used. The technique is based on elicitation from the decision maker or relative of *pairwise* judgements of the importance of the different attributes of interest. From these *pairwise* judgements, a priority ordering of the attributes of interest can be derived, together with a measure of the expert inconsistency. What is appealing with this method is that while the mathematical foundations of the method are by no means trivial, the use of the method for preference elicitation is straightforward and simple (Vokál *et al.*, 1997), and commercial software packages are available (e.g., Forman and Saaty, 2009). This approach also enables the expression of probability estimates in words and their subsequent transfer to numbers (Table 4.1).

Table 4.1: Qualitative criteria for expressing events in terms of probability of occurrence (Mahn, 1996).

Expression describing an event or process	**Probability of event occurring per year**
Highly probable	$> 10^{-2}$
Medium probable	10^{-2} to 10^{-4}
Low probable	10^{-4} to 10^{-6}
Not credible	$< 10^{-6}$

Step 9: Documentation

An essential element of a formal elicitation process is thorough documentation of all aspects of the process, the judgements acquired, and the rationale and basis for the judgements. The reasons for documenting the use of expert judgement for technical problems are derived from the following objectives:

- To improve decision-making associated with public policy.
- To enhance communication.
- To facilitate peer review appraisal, and acceptance.
- To recognise and minimise biases in expert judgement.
- To indicate the current state of knowledge about important technical and scientific matters.
- To provide a basis for updating that knowledge.

The availability of such documentation supports a broader understanding and acceptance of what was undertaken.

In the US Yucca Mountain project, formal procedures for documentation of expert judgement were part of the normal (QA) procedures for TSPA development, even where formal expert elicitation was not used. In particular, a systematic form of documented expert judgement was established for FEP screening and scenario development (Freeze, 2005). A team approach was used to provide consistency in the identification and screening of FEPs. Estimation of the probability of scenarios composed of the FEPs was part of the screening process. The FEP Team included a FEP Team Lead (FTL) and FEP Experts. It was responsible for maintaining the FEP list needed for the TSPA License Application (TSPA-LA), ensuring consistent treatment and documentation of FEPs in TSPA-LA documentation. This FEP Team was supported by Analysis and Model Report (AMR) Leads and by Subject-Matter Experts (SMEs). The SMEs are most technically knowledgeable about individual FEPs, and are responsible for developing the screening decisions, technical bases and documentation. The screening criteria were based on the probability and consequences of FEPs. The probability was quantified, where possible, but non-quantitative arguments were also used.

Similarly, in the Swedish programme (SKB, 2006), information based on expert judgements has been provided either in the form of reports written by one or several experts or as decisions made by generalists, e.g., the screening of FEPs or the selection of scenarios. Formal questioning of a panel of experts has not been employed. In general, no formal rules for the selection of experts have been applied. The generalists in the assessment core team provide a large fraction of the expert judgements. These individuals have been working with the safety of the KBS-3 system for a number of years and are, therefore, among the most experienced individuals available on the various aspects of the analysis of the system. This does, however, also imply a risk of bias, stressing the importance of external reviews of the material developed within the project. The scenarios, such as canister fail due to corrosion, isostatic overpressure or shear movements, buffer failure due to extreme ice sheets, movements in boreholes or other unspecified reasons, were defined without consideration of their likelihood.

4.4 Summary and Recommendations

The practice in the Czech programme of quantification of scenario probability in the preliminary PA to support the development of a DGR can be summarised as follows:

- Premature failure of the proposed carbon steel canisters after hundreds of years does not significantly affect the design performance of the DGR. It has been assumed that any hidden initial canister defects would have no significant effect on PA results, and the probability of such defects occurring can be taken as one.
- The probability of occurrence of natural events that could significantly affect performance of a DGR is considered to be negligible, as regulatory siting requirements rule out consideration of areas where such natural events could occur.
- No attempt has been made to quantify the probabilities of human-induced scenarios – siting requirements ensure that such probabilities are minimised.

Whether or not expert judgement will be used to estimate scenario probability is not an issue because the nature of the problem often does not allow for any other means to be applied, or expert judgement will be applied in combination with data from the geological and/or historical record. The issue is whether the expert judgement will be obtained and used with a formal, semi-formal or *ad hoc* approach. The main problem with informal approaches is that it can be difficult to provide transparency of the reasoning by which experts come to their opinions and quantify them.

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.

5 Conclusions (GSL)

This document reports on activities performed within Topic 2 of PAMINA WP2.2C. The aim of WP2.2C is to evaluate methods for the treatment of uncertainties associated with scenarios, that is, uncertainty about what might happen in the future to the disposal system. The task comprises three high-level topics that need to be considered in addressing scenario uncertainty: review of scenario development methodologies (Topic 1), quantification of scenario probability (Topic 2, this report), and use of formal expert judgement techniques for scenario conceptualisation (Topic 3).

This report has been assembled by GSL, and is made up from contributions by GSL (international review), VTT (review of practice in Scandinavia), and NRI (review of practice in the Czech Republic).

This report 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 and features is stylisation necessary and why?

The report also reviews regulation on the topic of scenario probability.

Scenario definition and classification

Scenarios can be considered as broad descriptions of alternative futures of the waste disposal system. Uncertainties concerning scenario likelihood can be treated using either deterministic (single value) approaches or probabilistic (sampling) approaches.

Scenarios are often classified based on their probability of occurrence and on the likelihood of the FEPs comprising the scenarios:

- *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, this scenario is assumed to have a probability of one.

- *Altered evolution 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.

The probability of scenarios can be evaluated and discussed in a safety case in one of three ways: quantitatively, qualitatively, or not at all in the case of stylised scenarios.

Question 1: Under what circumstances is probability estimation feasible?

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 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 TSPAs use PDFs for parameters that characterise relevant FEPs to define the probability of occurrence of all scenarios considered.
    - ➢ WIPP: undisturbed performance, mining, drilling.
    - ➢ Yucca Mountain: nominal case, early waste package/drip shield failure cases, igneous intrusion/eruption cases, seismic ground motion/fault displacement cases.
- In the 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.

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.

Alternatively, if the probability of “scenario-forming” FEPs can be reasonably determined, the probability of the scenario can be defined. Approaches that can potentially be used to determine FEP probabilities include:

- Derivation from observations of past events and existing conditions.
- Sampling a model of the physical system using Monte Carlo simulations.
- Use of a probability model (e.g. Poisson).
- Use of expert judgement, ideally through a well developed expert elicitation process, particularly where data are scarce or where safety case results depend strongly on probability. 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.

Similar approaches can be used to define PDFs of FEP characteristics for use in probabilistic calculations.

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.

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

We illustrate the reasons why probability estimation may not be necessary or not worthwhile via 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. Uncertainties that cannot be reliably quantified should be addressed through conditional risk calculations and qualitative reasoning.

No attempt is usually 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 ICRP's position that it is inappropriate to include the probability of future human actions in a quantitative performance assessment for comparison with dose or risk constraints. 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.

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. 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*".

- 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.

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.
- 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.

Overall conclusion

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.

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