Radioactive Waste Management

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Management of Uncertainty in Safety Cases and the Role of Risk

Workshop Proceedings
Stockholm, Sweden
2-4 February 2004

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Hosted by
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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full member. NEA membership today consists of 28 OECD member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

FOREWORD

The development of radioactive waste repositories involves consideration of how the waste and the engineered barrier systems will evolve, as well as the interactions between these and, often relatively complex, natural systems. The timescales that must be considered are much longer than the timescales that can be studied in the laboratory or during site characterisation. These and other factors can lead to various types of uncertainty (on scenarios, models and parameters) in the assessment of long-term, post-closure performance of waste management facilities. This report includes a synthesis of the plenary presentations and the discussions that took place at the workshop organised under the auspices of the NEA Integration Group for the Safety Case (IGSC) on the “Management of Uncertainty in Safety Cases and the Role of Risk”.

Previous NEA activities have examined some of the issues involved in the treatment of uncertainty. A workshop was organised in Seattle in 1987 on “Uncertainty Analysis for Performance Assessments of Radioactive Waste Disposal Systems”. One of the conclusions was that uncertainty analysis must be part of an overall system performance assessment and that a systematic approach should be adopted in conducting uncertainty analyses. The NEA Probabilistic Safety Assessment Group (PSAG) has discussed issues associated with the use of probabilistic codes to calculate risk, including a series of intercomparisons between different codes. The NEA Integrated Performance Assessment Group (IPAG) has also examined how uncertainties have been addressed in assessments, from both the regulators' and the implementers' perspectives. The uncertainties associated with the evolution of the disposal system must be appropriately considered and managed throughout a repository development programme. At each stage of a stepwise development programme, decisions should be based on appropriate levels of confidence about the achievability of long-term safety, with the current level of technical confidence established through uncertainty analysis.

Managing uncertainties and establishing levels of confidence can be approached in different ways. One part of the overall uncertainty management process is a quantitative assessment of system performance, but other elements of the safety case such as the use of complementary (e.g. qualitative) lines of evidence will also contribute to uncertainty management. Overall, a clear strategy for dealing with these uncertainties will need to be explained within the safety case for a waste management facility and in the supporting integrated performance assessment.

Assessment programmes in a number of countries are reaching key stages in the development of safety cases, and regulations and regulatory guidance are also under review in several countries. To build upon the lessons learnt from these developments and the earlier NEA activities, the 2004 workshop in Stockholm was organised to provide an opportunity to hold focused discussions on approaches to making decisions under uncertainty.

ACKNOWLEDGEMENTS

On behalf of all participants, the NEA wishes to express its gratitude to the Swedish Radiation Protection Authority (SSI), which hosted the workshop in at RÅNÄS Castle, Stockholm, Sweden on 2-4 February 2004.

Special thanks are also due to:

- The members of the Workshop Programme Committee[1] who structured and conducted the workshop.
- Roger Wilmot, Galson Sciences Limited (United Kingdom) who helped the Secretariat and the programme committee in drafting the workshop synthesis.
- The working group chairpersons and rapporteurs (see Annexes) who led and summarised the debates that took place in the four working groups.
- The speakers for their interesting and stimulating presentations and all participants for their active and constructive contribution.

The Workshop was sponsored by SSI who provided funds for hosting the meeting, supported external participants and a dinner for participants. Additional support was provided by Posiva, SKI, and HSK who made funds available for the participation of outside experts. In addition, SKI contributed to the costs of preparing the Workshop synthesis and proceedings, and SKB sponsored a dinner for participants.

1. Programme committee: Björn Dverstorp (Chairman, SSI, Sweden), Mikael Jensen (SSI, Sweden), Patrick J. O'Sullivan (NRG, Netherlands), Philippe Raimbault (DGSNR, France), Klaus-Jürgen Röhlig (GRS-Köln, Germany), Eva Simic (SKI, Sweden), Juhani Vira (Posiva, Finland), Sylvie Voinis (NEA, France) and Roger Wilmot (Consultant, Galson Sciences Ltd, UK).

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INTRODUCTION

Background

Deep geological repositories aim to protect humans and the environment from the hazards associated with radioactive waste over timescales often up to several thousand or even a million years. Radioactive waste management thus involves a unique consideration of the evolution of the waste and engineered barriers systems, and the interactions between these and geological barriers over very long periods of time. Over long enough timescales, however, even the most stable engineered materials and geological environments are subject to perturbing events and changes that are subject to uncertainties.

The uncertainties associated with the evolution of the disposal system must be appropriately considered and managed throughout a repository development programme. At each stage of a step-wise development programme, decisions should be based on appropriate levels of confidence about the achievability of long-term safety, with the current level of technical confidence established through uncertainty analysis. The uncertainties and the potential for reducing them in subsequent development phases should be described in the safety case at each stage.

Managing uncertainties and establishing levels of confidence can be approached in different ways. One part of the overall uncertainty management process is a quantitative assessment of system performance, but other elements of the safety case such as the use of complementary (e.g. qualitative) lines of evidence will also contribute to uncertainty management (OECD/NEA, 2004). Other issues, including policy, social context, availability of resources and decision-making timetables, also affect choices and the presentation of a safety case.

A safety case will place most emphasis on the evaluation and argumentation of the expected performance of a waste management facility by taking into account the level of uncertainties at the relevant stage of development. A safety case will also take into account less likely events and scenarios, but with less emphasis than for the expected evolution.

In a number of OECD countries, regulations and regulatory guidance for the management of radioactive waste include criteria that require an explicit calculation of long-term risk. Waste management programmes in these countries therefore need to assess the probability of different features, events and processes affecting a management facility in order to weight the consequences of different potential evolutions; other types of uncertainty may also be expressed as probabilities. The regulators in these countries need to assess the reasonableness of the probabilities and other assumptions made in safety cases presenting risk assessments. Other countries do not have explicit requirements for calculating risk or assessing probabilities, and safety cases and regulatory assessments in these countries adopt other approaches to considering the same uncertainties.

The fact that decision making is not based on a numerical value for uncertainty is witnessed by the fact that, even though probabilistic assessments of safety of nuclear power plants (NPP) have been in use for many years, no such facility has ever been licensed on the result of only a probabilistic assessment.

Workshop initiative

Previous NEA activities have examined some of the issues involved in the treatment of uncertainty. A workshop was organised in 1987 in Seattle, on "Uncertainty analysis for performance assessments of radioactive waste disposal systems", and one of the conclusions was that uncertainty analysis must be part of an overall system performance assessment and that a systematic approach should be adopted in conducting uncertainty analyses. The Probabilistic Safety Assessment Group (PSAG) discussed issues associated with the use of probabilistic codes to calculate risk, including a series of inter-comparisons between different codes (OECD/NEA, 1997a). The Integrated Performance Assessment Group (IPAG) also examined how uncertainties were addressed in assessments, from both a regulator's and implementers' perspective (OECD/NEA, 1997b, 2002a).

To build upon the lessons learned from these earlier activities, and to provide an opportunity for a focused discussion on approaches to making decisions under uncertainty, a Workshop on the general theme of risk characterisation was proposed by the Swedish Radiation Protection Authority (SSI) at the 3rd IGSC meeting in October 2001and approved at the 4th IGSC meeting in November 2002.

The aim of the workshop on the "Management of Uncertainty in safety cases and the Role of Risk" was to discuss the issues associated with different approaches to treating uncertainties in safety cases for radioactive waste management facilities, and specifically how concepts of risk can be used in both post-closure safety cases and regulatory evaluations. The workshop was held in Stockholm 2-4 February 2004.

Report structure

Following this introduction, these proceedings include the Workshop Objectives and Structure that provided participants with a framework for the presentations and discussion. The Workshop included both plenary presentations and working group sessions. The Proceedings present summaries of the plenary presentations, syntheses of the working groups prepared by rapporteurs, and a summary of the final workshop discussion. These summaries are followed by conclusions from the workshop. A list of references and Working Group participants are also included.

WORKSHOP OBJECTIVES AND STRUCTURE

The **overall aim of the Workshop** was to create a platform in order to better understand different approaches to managing uncertainty in post-closure safety cases and regulatory approaches in different national waste management programmes.

The **principal objectives of the Workshop** were to:

- To identify common elements in different approaches for managing uncertainty.
- To facilitate information exchange and to promote discussion on different technical approaches to the management and characterisation of uncertainty and on the role of risk.
- To explore the merits of alternative approaches to risk-informed decision making.
- To identify the potential for further developments of methods or strategies to support the management of uncertainties.

The Workshop was organised into plenary sessions and working group discussions:

The **first plenary session** focused on establishing a framework for understanding the management of uncertainties and the use of risk. It comprised oral presentations drawing on a range of experience from both active participants in the development and assessment of safety cases and keynotes presentations by external participants involved in risk management in other sectors.

The **working group discussions** covered three technical themes:

- **WG 1: Risk management and decision making**

  This theme examined what type of safety case would best serve decision makers. Alternative approaches to risk-informed decision making, and the role of stakeholders and experts in these approaches, were discussed. The concept of risk and its different aspects or dimensions (social, technical, mathematical) was examined. Overall, this theme considered the management of risks as well as the assessment of risks.

- **WG 2: Regulatory requirements and review of uncertainty and risk in safety cases**

  This theme examined processes for regulatory assessment of safety cases. Approaches to setting standards and determining appropriate regulatory end-points were considered. Methods for evaluating the results of, and finding weaknesses in, risk assessments and other assessments of uncertainty were addressed. Topics such as the role of risk in regulations, the types of information required by regulators, the role of qualitative information in safety cases, and the importance of calculated risk in comparison to other lines of reasoning were discussed.

- **WG 3: Practical approaches and tools for the management of uncertainties**

  This theme addressed issues concerning the characterisation and calculation of risk, and other strategies for the treatment of uncertainties. Topics such as the selection of scenarios and the assignment of probabilities, the use of expert judgements, and the presentation of information on uncertainties and risk were examined.

The aim of the working groups was to develop an understanding of the specific issues, and to identify any further activities that will support the development and/or evaluation of safety cases.

The **round up plenary session** brought together information and conclusions from each of the working groups. Common elements in the different approaches to treating uncertainty and risk were identified, along with potential further developments of methods or strategies to support risk characterisation and assessment. This session included presentations by rapporteurs from each working group, and an open discussion of the themes and conclusions by all the participants.

PLENARY PRESENTATIONS

Introductory remarks

The Workshop began with welcoming remarks from Lars-Eric Holm on behalf of SSI who were hosting the Workshop.

Sylvie Voinis welcomed participants to the Workshop on behalf of the OECD/NEA, and gave a presentation summarising the conclusions from previous NEA activities relating to the treatment of uncertainties. One of the earliest activities was a meeting in Seattle in 1987 at which the importance of treating uncertainties in assessments of post-closure performance of disposal facilities was highlighted. This early recognition of the issue has been developed through a series of NEA meetings and workshops in subsequent years. The Probabilistic Safety Analysis Group (PSAG) played an important role in encouraging debate about different approaches and also organised a series of code intercomparison exercises (OECD/NEA, 1997a). Other key activities include initiatives by the Integrated Performance Assessment Group (IPAG) (OECD/NEA, 1997b, 2002a), workshops on confidence building (OECD/NEA, 1999), and the handling of timescales (OECD/NEA, 2002b), and the ongoing development of the Safety Case Brochure (OECD/NEA, 2004).

These activities have led to some broad conclusions about how uncertainties should be treated in a safety case:

- The safety case informs decisions at each stage of a step by step decision-making process. There is therefore a trend towards safety cases providing a statement on why there is confidence in the results presented, and on the sufficiency of the safety case for the decision at hand. With that perspective, such a statement should acknowledge the existing uncertainties, their significance at the present stage of assessment, and the future steps required to reduce uncertainty.
- Uncertainties should be recognised as an inevitable aspect of radioactive waste management systems, and these uncertainties will increase with the timescale considered.
- Uncertainties should be treated explicitly, and a systematic approach will aid understanding.
- A combination of deterministic and probabilistic approaches may be appropriate. Decision making is not based on a numerical value for uncertainty; and there is a need for clarifying the role of each approach in the safety case.
- A range of scenarios need to be considered in order to explore uncertainties. The issue of human intrusion has a special place within the scenarios considered.

Confidence in the safety case will be supported by a clear statement on data quality, clear justifications of assumptions and discussion of the sensitivities of the system performance to data uncertainty. A range of arguments is important in treating uncertainties and developing a safety case. In particular a mixture of quantitative and qualitative arguments will engender confidence in both the provider and the reviewer. Overall, the Safety case can best fulfil the requirements of decision making by including a statement on why there should be confidence in the analysis of performance and associated uncertainties.

Concepts of risk

Following the introductory remarks, the Workshop continued with two plenary presentations discussing concepts of risk from both a technical and social perspective.

Risk in Technical and Scientific Studies: General Introduction to Uncertainty Management and the Concept of Risk

George Apostolakis (MIT) presented an introduction to the concept of risk and uncertainty management and their use in technical and scientific studies. He noted that Quantitative Risk Assessment (QRA) provides support to the overall treatment of a system as an integrated socio-technical system. Specifically, QRA aims to answer the questions:

- What can go wrong (e.g., accident sequences or scenarios)?
- How likely are these sequences or scenarios?
- What are the consequences of these sequences or scenarios?

The Quantitative Risk Assessment deals with two major types of uncertainty. An assessment requires a "model of the world", and this preferably would be a deterministic model based on underlying processes. In practice, there are uncertainties in this model of the world relating to variability or randomness that cannot be accounted for directly in a deterministic model and that may require a probabilistic or aleatory model. Both deterministic and aleatory models of the world have assumptions and parameters, and there are "state-of-knowledge" or epistemic uncertainties associated with these. Sensitivity studies or eliciting expert opinion can be used to address the uncertainties in assumptions, and the level of confidence in parameter values can be characterised using probability distributions (pdfs). Overall, the distinction between aleatory and epistemic uncertainties is not always clear, and both can be treated mathematically in the same way.

Lessons on safety assessments that can be learnt from experience at nuclear power plants are that beliefs about what is important can be wrong if a risk assessment is not performed. Also, precautionary approaches are not always conservative if failure modes are not identified. Nevertheless, it is important to recognise that uncertainties will remain despite a quantitative risk assessment: e.g., is the scenario list complete, are the models accepted as reasonable, and are parameter probability distributions representative of the current state of knowledge? As a consequence, decisions should be risk-informed, not risk-based, and traditional approaches still have a role to play.

As an example of a risk-informed approach, guidelines from the USNRC for the acceptance of proposed changes at NPPs were presented. These acknowledge that the level of technical review and management attention given to proposals will vary according to both the estimated core damage frequency (CDF) and the change in frequency resulting from the proposed change (ΔCDF). Different criteria apply to different regions on a plot of CDF vs. ΔCDF, but the numerical values defining the regions are indicative and the boundaries between them are not interpreted definitively.

Finally, two interpretations of the defence-in-depth (DiD) approach were presented. The *structuralist* approach applies defence-in-depth within the regulations and in the design to provide specific answers to the question of "what happens if this barrier fails?" In contrast, the *rationalist* approach applies defence-in-depth across the range of safety features, taking account of the uncertainties in the scenarios that such features are designed to mitigate.

Discussion of this presentation focused on the role of the regulator in setting the assessment criteria. In the context of nuclear power plant (NPP) safety cases, the USNRC sets criteria for core damage frequency and releases and takes responsibility for translating these into individual and population risks. In other words, the assumptions and parameter values regarding exposed groups and their behaviour are determined by the regulator rather than by the proponent.

Risk perception as a factor in policy and decision making

Lennart Sjöberg (Centre for Risk Research, Stockholm School of Economics) discussed the ways in which perceptions of risk can play a role in policy and decision making. The commonly stated view of risk perception is based mainly on American surveys from the end of the 1970s, which emphasised the importance of emotional factors such as "dread", and also social trust, for explaining perceived risk. However, the detailed results from these studies show that only about 20% of the variance across respondents is explained by "dread" and that overall attitude to issues such as nuclear power and related moral convictions actually explain more of the variance. Trust in science is more important than social trust.

The factor that is most important to people is the size of the potential consequences of accidents. The benefits of developments may be recognised but are seen as less important than the associated risks, and risk in turn tends to be interpreted solely in terms of consequence.

The overall conclusion from recent work is that that the public reacts on the basis of moral and ideological beliefs rather than emotions, and that people will see the wider context for decisions if allowed to do so. Risk communication must be responsive to people's beliefs and values and not on apparent influences derived from a weak model of perceptions.

In the discussion of this paper, Professor Sjöberg noted that some stakeholders do indeed have an "emotional" response, but that this is a small group and not the majority of the public. In practice, the attitudes of the general public to risk are similar to those of local politicians.

There was discussion of how public attitudes were influenced by the fact that the recipients of the benefits may not be the sufferers of risk – this was noted as a key issue in debates about deep disposal facilities. Professor Sjöberg noted that there does not appear to be a big difference in the attitude of the public to individual and societal risks.

Expert judgement

The collection of expert judgements for environmental risk studies

The plenary presentations continued with a presentation by Steve Hora (University of Hawaii) on the role of experts and expert judgements in risk assessments. There are four key areas in which experts play a role in assessments and the development of the safety case:

- review of the work;
- advice about the work;
- performance of the work;
- testimony or provision of knowledge about models, parameter values, etc.

Steve Hora's presentation was focused on the last of these areas and specifically on the use of structured approaches to quantifying information for use in assessment models.

The use of experts to quantify information is favoured in situations where there are conflicting sources, laboratory-scale data but field-scale uncertainties, limited evidence or information on uncertainties, and unverified models and procedures. Expert judgements are important where these situations correspond with information that is critical for determining risk, or where public scrutiny and potential legal action are anticipated.

Expert judgements attempt to record the information available at a particular time, and as with other approaches may need to be updated as more information becomes available. Judgements are required on the uncertainties associated with the values as well as the values themselves. Probability is viewed by many as the natural language for quantifying uncertainties and allows both for the quantification of "what we know", but also of "what we know we do not know". The derivation of probability distribution functions (pdfs) is therefore a common goal of expert judgements.

The selection of experts is important, and the selection process may receive as much scrutiny as the judgements themselves. Three is regarded as the minimum number of experts required if there is any controversy about the issue concerned. Conversely, 10 or 12 experts would be a reasonable maximum, and, in many cases, there would be significant redundancy associated with the results from so many experts.

The opinions expressed by experts can suffer from different types of bias. Selection of experts should help to eliminate motivational bias arising from an economic or political interest in the outcome of the assessment. Another type of bias is overconfidence, or the tendency to assign too little uncertainty. Appropriate training for the experts can help to reduce this type of bias and instil confidence in the process of eliciting pdfs.

The differences between experts may be greater then the uncertainty expressed by individual experts. It is therefore also important to have a documented approach to combining results from different experts. Available approaches include reaching a consensus between experts, simple linear combination of probabilities, or differential weights that attempt to take account of the experts' knowledge through responses to test questions. The setting of such questions to calibrate experts can be done for test cases or in training, but is difficult for real elicitation problems.

The discussion of this presentation on expert judgement included questions about whether it was ever possible to find truly independent experts. Steve Hora agreed that for many topics relevant to assessments the majority of technically qualified experts were likely to have some past or present involvement with assessment programmes. In such cases, it is important to avoid obvious biases and to document the experts background. There was also discussion of the number of issues that might be the subject of formal expert elicitation or judgements. Steve Hora noted that for the WIPP programme there were 6-8 issues considered in this way. He also noted that some of the practices used in formal expert elicitation, such as clear descriptions of assumptions and justifications, are useful even in less formal judgements.

Risk in regulations

Survey of the role of uncertainty and risk in current regulations

The overall aim of the Workshop was to provide a platform to better understand different approaches to managing uncertainty in different national waste management programmes. To provide participants with background information for understanding the different approaches, Roger Wilmot (Galson Sciences Ltd) gave a presentation on the role of uncertainty and risk in regulations and guidance in different countries. The aim of the presentation was to highlight both differences and similarities between the approaches used in different countries, and to introduce topics for discussion at the Workshop.

Regulations and guidance include both numerical and qualitative criteria relating to uncertainty and risk. Numerical criteria are relatively easy for compliance, although should not normally be used as the sole basis for determining safety. Qualitative requirements and criteria include issues such as transparency and traceability, quality assurance, sound science and engineering, and optimisation. Numerical criteria are almost always related to safety indicators, with dose and risk the most common. Other examples of numerical criteria include fluxes, concentrations and release rates. These may require that the regulations or guidance prescribe key assumptions about system characteristics, such as the type of biosphere assumed.

Regulations and guidance in different countries incorporate slightly different dose constraints for radioactive waste management facilities, but typically, the dose constraint is between 0.1 and 0.5mSv/yr. Where risk is used as the safety indicator, there is consistent use of a risk of 10^{-6}/yr of death or serious health effects for a representative individual.

Regulations differ in the extent to which they prescribe the activities to be considered for exposed groups or exposed individuals. Subsistence farming and groundwater extraction for drinking and irrigation are commonly required to be considered. Human intrusion is also acknowledged as an issue in most regulations, but there are differences in how it is required to be treated. Deliberate intrusion is generally specifically excluded.

All the regulations surveyed emphasise the importance of treating uncertainties in safety assessments, but there are differences in the extent to which the regulations prescribe the approach to be used. There are examples of regulations that require an explicit quantification of uncertainties, and others that require an implicit quantification through the use of variant scenarios. In regulations with a risk criterion, there is a requirement to consider the uncertainties associated with both the receipt and the effect of a dose.

An important difference between the regulations surveyed is in the scenarios that are specified for assessment. A normal evolution scenario is implicitly or explicitly specified in all cases, and many regulations require a separate treatment of human intrusion scenarios. Apart from these, there is little consistency in the terminology used to describe alternative scenarios, how these scenarios should be selected or the results integrated.

Finally, Roger Wilmot noted that only the regulations for the WIPP site require the use of probabilistic calculations (to calculate cumulative releases). The regulations for Yucca Mountain expect a probabilistic approach to be used (to calculate dose) and guidance in the UK indicates that probabilistic approaches can be used (to calculate risk). None of the other regulations or guidance surveyed indicates whether deterministic or probabilistic approaches are expected.

In the discussion of this presentation, Roger Wilmot clarified the differences between regulations over the individual protected by the numerical criteria. For deterministic assessments there is likely to be little difference between a representative member of the exposed group at greatest risk specified in some regulations (an extension of the critical group concept), and the reasonably maximally exposed individual (RMEI) specified in other regulations. For probabilistic assessments, there may be differences in calculated dose or risk if different assumptions about the location and characteristics of the protected individual are accounted for probabilistically.

Case studies

The Workshop continued with two plenary presentations describing the development of safety cases with different approaches to the treatment of uncertainties. Arnaud Grévoz (Andra) gave a presentation on the use of risk-management methods at Andra, and Abe Van Luik (USDOE) described the TSPA for Yucca Mountain.

Case study 1 – management of uncertainties and the role of risk in Andra's programme

Arnaud Grévoz (Andra) described the risk-management methods used in the "dossier 2001" programme for deep geological disposal in clay, and in the guidelines being developed for the 2005 dossier.

In France, the principal guidance for developing a safety case for deep geological disposal (RFS III.2.f) requires the definition of a "reference evolution" that encompasses "the foreseeable evolution of the repository as regards certain or very probable events", and the definition of "hypothetical evolutions" corresponding to the occurrence of random events. These evolutions are defined and analysed deterministically.

The radiation protection criterion in the French regulations is a dose for the "reference evolution" of 0.25mSv/yr. There are no predefined criteria for the altered evolutions, except that doses "*should be maintained well below levels liable to give rise to deterministic effects*". The use of risk as a safety indicator is considered as a possibility in the regulations, but in practice it is rarely referred to because, according to the RFS, "*it may imply a debatable equivalence between reducing the probability and reducing the exposure*". Instead of risk, therefore, the regulations recommend the assessment of consequences (doses) and a case-by-case judgement of acceptability.

In Andra's 2001 assessment programme for deep geological disposal in clay, the aim was to address some uncertainties by means of risk analysis tools commonly used in other industries. The approach used was Failure Mode and Effects Analysis (FMEA), which is widely tested and accepted in other fields. Andra's use of this approach categorised uncertainties in terms of:

- uncertainties in the understanding of the phenomenology;
- uncertainties in the way system evolution is modelled and predicted;
- uncertainties in the occurrence of future events (climate change, human intrusion, etc.).

Some uncertainties (especially the first and third types) could be quantified and expressed as risks in the conventional sense. This in turn allowed the key risks and uncertainties to be recognised. This treatment of uncertainties and ordering of risks is called AQS (qualitative safety analysis).

In AQS, the expected performance of each safety function within a disposal system (e.g., protection of the waste packages, maintenance of a diffusive environment) is assessed. Uncertainties in this performance are expressed as possible causes of failure (i.e., not performing as expected) and these causes were given a relative likelihood of occurrence. Only those uncertainties that could affect directly a safety function were treated using this "risk" approach. Other uncertainties were addressed through choices of models and parameters, using a "cautious but reasonable" approach to take account of the uncertainties.

Feedback from the NEA peer review of Andra's programme and from national and internal reviews was positive towards the development of qualitative safety analysis, but noted that the use of methods such as FMEA does not easily allow specific of long-term performance assessment to be taken into account (e.g., degradation of a safety function over time).

The experience gained from the use of AQS in the dossier 2001 has been used in planning dossier 2005. The analogy between uncertainties and risks will be maintained but will be treated in a more systematic and simplified manner. All types of major uncertainties will be addressed, but as little reference as possible will be made to probabilities. A qualitative evaluation of the level of each uncertainty will be made but not used to rank long-term risks. Probabilities will be avoided because they can be difficult to assess over long timescales (e.g., the probability of a borehole over 1 million years), because the situation considered does not have a probability (e.g., "what-if" scenarios), and because the regulations do not encourage use of probabilities in a deterministic context.

In conclusion, Arnaud Grévoz noted that the management of uncertainties can take various forms according to both the objectives of the assessment and the stage reached by the research programme. Risk has different meanings in different contexts, but the notion of risk can be used even in deterministic, non risk-based approaches. Similarly, although probabilities are difficult to handle and may lead to misunderstandings, probabilistic calculations can have a role even in a deterministic assessment (e.g., sensitivity calculations to refine judgements on the possible coupled effects of uncertainties).

In the discussion of this presentation, Arnaud Grévoz underlined the apparent paradox that a deterministic approach must take into account the probability of the situations analysed, so as to judge if they are important or not. Therefore, there is no purely "deterministic" approach as such.

Case study 2 – treatment of uncertainty in the US Department of Energy's Yucca Mountain Repository Total System Performance Assessment (TSPA) with a risk criterion

Abe Van Luik (USDOE) described the treatment of uncertainty in the Total System Performance Assessment (TSPA) for the Yucca Mountain Repository. One of the main purposes of the TSPA is to provide decision makers with a meaningful display of the effects of uncertainty on our understanding of the future behaviour of the disposal system.

However much information is obtained about the system, uncertainty is unavoidable. In designing an uncertainty analysis, however, it is important to remember two key points:

- Uncertainty that is not characterised in the model inputs will not propagate through the system model.
- Not all input uncertainty matters for all performance measures.

Internal and external (including international and regulatory) reviews of the earlier TSPA that supported the Site Recommendation considered that there was an inconsistent treatment of uncertainties across the disciplines feeding into the TSPA. The project's response to these reviews was to prepare an "Uncertainty Analysis and Strategy" document and guidance. The overall goal of the uncertainty strategy is an analysis approaching realism. However, the focus on a realistic treatment of uncertainty is not necessarily the same as a full understanding of realistic performance. It is therefore appropriate to use simplified models, broad uncertainties and conservatisms providing these are justified and explained. A team approach of scientists and analysts is a key element of the uncertainty strategy.

A formal process has been established for selecting parameter values and distributions for TSPA. For uncertain parameters that are important to system performance, the goal is to represent the "full range of defensible and reasonable parameter distributions rather than only extreme physical situations and parameter values".

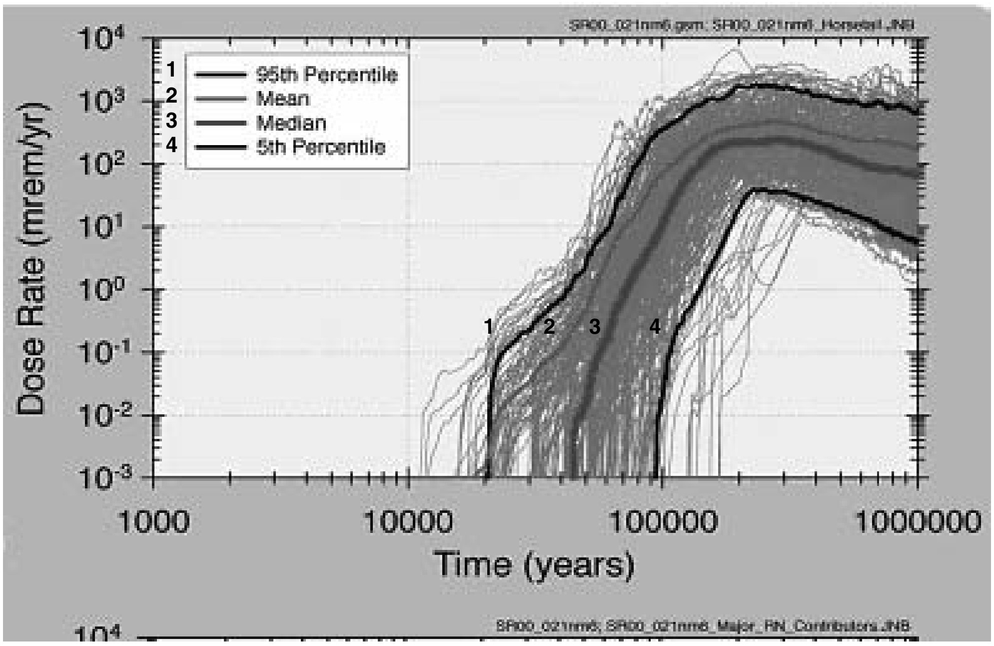
A structured approach has also been established to take account of alternative conceptual models (ACM). If two or more ACMs show different subsystem performance, abstractions are developed for both and used in TSPA calculations to determine any differences in system-level performance. If there are significant differences, the options are to include multiple ACMs in TSPA with a weighting, or to consider a conservative choice of model.

Abe Van Luik illustrated the approach to the treatment of uncertainty with examples from the Probabilistic Volcanic Hazard Analysis (PHVA), which was undertaken to develop a defensible assessment of the volcanic hazard at Yucca Mountain, with quantification of the uncertainties. A range of temporal and spatial probability models was used to characterise future volcanic occurrences. The output from these provides hazard frequencies and event descriptions that serve as inputs to consequence models.

Overall confidence in the treatment of uncertainty in TSPA comes from understanding uncertainty in the underlying data, models, and parameters, and documenting the propagation of these uncertainties through the TSPA. Sensitivity analysis shows that many uncertainties don't matter to system performance. However, once models and input distributions are complete, uncertainty in model results provide useful insights into model behaviour and system understanding.

Figure 1 shows some probabilistic results from the Yucca Mountain TSPA. These show that uncertainty in PA results does not necessarily always increase with time. For most measures of interest, uncertainty will reach a maximum and then decrease as the occurrence of the controlling processes (e.g., waste package degradation or radioactive decay) becomes more certain.

Figure 1. **Illustrative results of a probabilistic analysis for Yucca Mountain (TSPA-SR Rev 00 ICN 01 Figure 4.1-19a).**



In the discussion of this presentation, Abe Van Luik clarified that, although there is a 10 000-year regulatory period for some TSPA calculations, the Environmental Impact Assessment requires that calculations are carried out for longer timescales. An overall limit of 10^6 years represents the period of geological stability.

Risk assessments in other industries

The use of risk in decision making and accounting for uncertainties in safety assessments is not restricted to the nuclear industry. To provide a broader perspective to the discussions at the Workshop, Felix Gmünder gave a plenary presentation describing the regulatory regimes for major accident hazards and nuclear installations in Switzerland.

Risk considerations in the domains of protections against major accidents in comparison with risk control for nuclear power plants

Felix Gmünder (Basler & Hofmann) outlined the Ordinance on the Protection against Major Accidents (OMA), which seeks to protect the public and the environment from the consequences of major accidents, and to reduce risks through a reduction in hazard potential, prevention of major accidents, and the mitigation of accident consequences. The OMA applies to facilities with certain quantities of hazardous substances, products or special wastes, facilities with dangerous natural or genetically modified micro-organisms in containment and to certain transport routes (railway lines, transit roads and the Rhine). The presentation focused on the risks posed by facilities holding large quantities of ammonia.

A key element in the enforcement of the OMA is the provision of guidance documents. These provide facility owners with guidance for performing hazard and risk assessments that meet the requirements of the OMA, and harmonise enforcement throughout cantons and industries. The guidance documents available include handbooks that explain the technical hazard and risk assessment process, manuals that are specific to one type of installation and provide detailed technical information on how to perform hazard and risk assessments for that particular installation, and case studies that provide transferable models and data. One reason for the enforcement approach adopted for the OMA is the large number of sites affected. It would be unmanageable for all sites to develop independent approaches to safety assessment or for regulators to assess different approaches.

A hierarchical approach to documentation and assessment is used, depending on the amount of hazardous material held and the potential consequences. If a risk assessment is performed and the calculated risks are unacceptable, then risk management measures must be instigated. A key response to the OMA has been a reduction in hazard potential through a reduction in the amount of hazardous materials used and stored at sites.

In the case of nuclear installations, the increasing age and extent of back-fitted systems means that risk control plays an increasing part in licensing and supervision. A new legal framework contains the basis for risk-informed supervisory decision making, taking account of risk information and uncertainties in all areas. The basis for different supervisory approaches is the calculated core damage frequency (CDF), but the responses are also based on the magnitude of releases associated with the release scenarios.

Table 1 summarises some of the differences and similarities between the approaches to chemical and nuclear risks.

Table 1. **Differences in Decision-Making Approaches in Switzerland (Chemical vs. Nuclear)**

	Chemical hazards	Nuclear Power Risk
system characteristics	Low to medium hazard potential. Hazard potential can be reduced.	Large hazard potential. Hazard potential difficult to reduce.
decision-making approach	Hazard control through risk reduction.	Risk control through safety improvements.
risk analysis methodology	Probabilistic, point estimate estimation.	Probabilistic, distributed input- and output parameters.
treatment of uncertainty	Implicit, through reduction of risk.	Explicit. Risk criteria take into account uncertainty.
backfitting rule	State of the art technology determines appropriate measures to reduce risk. Probabilistic target to determine supplementary safety measures to be implemented.	Probabilistic target for minimum safe operations. State of the art of backfitting technology must be implemented regardless of probabilistic target.

In the discussion of this presentation, Felix Gmünder noted that political decision making is always a final step in safety assessments. He also clarified that there is a 10^{-2} risk aversion factor included within the OMA tolerability criteria, and that analyses take account of potential human errors (e.g., incorrect switch operation) but not the overall safety culture at the facility.

Regulatory criteria

In many countries, there are generic regulations and guidance applicable to facilities for radioactive waste management. In some countries, for example the USA, these generic regulations are supplemented by site-specific regulations. In other countries, additional, more detailed regulations and guidance are under development ahead of license applications. A plenary presentation by Klaus Röhlig (GRS) summarised the GRS proposal for revised Safety Criteria in Germany, and a presentation by Esko Ruokola (STUK) described the way in which unlikely events and uncertainties are treated in Finnish regulations.

Development of safety criteria in Germany: aims, processes and experiences

Klaus Röhlig (GRS) described the basis for proposed changes in the regulations and safety criteria for radioactive waste management facilities in Germany. Deep disposal is foreseen for all types of radioactive waste and there is a political preference for a single repository. The proposed revisions to the safety criteria are based on this concept and anticipate a multi-barrier approach but with an emphasis on the geological barrier.

Klaus Röhlig's presentation concentrated on the post-operational criteria, but the proposed revisions to the regulations cover other aspects and timescales. The proposed criteria are based on:

- IAEA Regulations e.g. Fundamental principles for the safe handling of radioactive wastes.
- The act on Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.
- Norms of the European Union.
- ICRP regulations.
- OECD/NEA reports, most notably: development of the Safety case.

Draft criteria address the following topics:

- Safety principles.
- Radiation protection objectives for the operational & post operational phases.
- Site requirements.
- Design and implementation.
- Criteria for operational phase.
- Criteria for post-operational phase.

With regard to the long-term safety demonstration, the draft criteria specify

- Timeframe for long-term safety demonstration.
- Long-term safety analyses:
  - Scenario analysis.
  - Consequence analyses.
  - Data acquisition.
  - Demonstration of compliance with protection objectives.

In addition, supporting technical guidelines e.g. on the demonstration of operational and post-operational safety, are also in preparation.

GRS's review of previous assessments and other studies on calculation endpoints concluded that one of the key issues is the extent of aggregation vs. disaggregation both with respect to combining different scenarios and to weighting likelihood and consequence. Klaus Röhlig noted that even the presentation of calculated dose can be viewed as a somewhat arbitrary aggregation. Determining the extent of aggregation in a calculation endpoint should take account of the practicalities of performing the assessment and communicating the results as well as the philosophy of protection objectives.

The conclusion of GRS's deliberations was that it would be desirable to have a dose constraint for the expected evolution and to weight likelihood vs. consequence for less likely scenarios. This approach leads to questions, however, as to which likelihood of receiving a dose is appropriate, even if uncertainties can be quantified. GRS's proposed criteria for natural processes and future human actions other than direct intrusion are, therefore:

- Likely scenarios: target 0.1 mSv/yr.
- Less likely scenarios: target 1 mSv/yr.

Compliance with these targets has to be demonstrated by means of probabilistic analyses; a target is considered to be met if certain statistical tolerance limits for the resulting distributions lie below the target. No quantitative criteria are proposed for direct human intrusion; guidance will be developed on the scenarios to be considered.

In addition to concerns about the use of risk because of the difficulties of defining and quantifying likelihood for scenarios and communicating results, Klaus Röhlig noted that the BMU's advisory committees have expressed serious concerns regarding approaches that appear to allow "compensating" severe consequences by weighing them with low likelihoods of occurrence. Potential exposures of more than 1 mSv/yr were seen as problematic regardless of the likelihood of occurrence.

In the discussion of this presentation, Klaus Röhlig confirmed that the proposed criteria would limit the timescale for the assessment to 10^6 years, since there is little credibility for integrated safety assessments beyond this period. He noted that GRS proposed to provide guidance on highly speculative aspects of assessments, such as the characteristics of the biosphere to be assumed.

There was further discussion about the appropriate likelihood to be used to account for uncertainties regarding short-term events. Klaus Röhlig stressed that, as well as avoiding the debate about "victim" versus "culprit" perspectives by adopting dose criteria; the proposed safety principles would require site selection to avoid regions where uncertain events such as volcanic activity could affect a repository.

Consideration of unlikely events and uncertainties in the Finnish safety regulations for spent fuel disposal

Esko Ruokola summarised the role of unlikely events and uncertainties in Finnish safety regulations. STUK guidance distinguishes several timescales for assessments:

- Operational period. Tens of years.
- Reasonably predictable future. From closure to several 10^3 yr.
- Era of extreme climate changes. From several 10^3 to a couple of 10^5 yr.
- The farthest future. Beyond a couple of 10^5 yr.

In the reasonably predictable future, boreal or temperate climate conditions will persist. Geological conditions are expected to be stable or change predictably, but considerable environmental changes will occur due to land uplift. The engineered barriers are required to provide almost complete containment of waste during this period, and retrievability of waste must be feasible. The radiation protection criteria are based on doses (or expected doses) to members of hypothetical critical groups from early failure scenarios.

The dose constraint for members of a self-sustaining community is 0.1 mSv/yr. For doses from unlikely events, there is an equivalent dose constraint (i.e. the calculated dose x probability of its occurrence must satisfy the dose constraint). STUK guidance requires several scenarios to be considered (assuming present lifestyles and climate conditions):

- use of contaminated water as household water;
- use of contaminated water for irrigation of plants and for watering animals;
- use of contaminated watercourses.

For larger populations, the average dose should not exceed 1-10 μSv/yr.

STUK guidance requires a number of unlikely events to be considered:

- boring a deep water well at the disposal site;
- core-drilling hitting a waste canister;
- substantial rock movement at or near the disposal site.

For the deep water well, there is a high probability that such well will exist at the repository's discharge area at some time, but a rather low probability that it will exist there in a given year (not more than 10^{-2}). The criteria theoretically allow quite high individual doses of around 10 mSv/yr, although these are still in the range of "natural" doses from water wells. STUK has concluded that this scenario can be analysed quantitatively and judged against the expected dose criteria.

Similarly, the core drilling and rock movement scenarios may be analysed and judged in a semi-quantitative, disaggregated manner. Definition of a stylised drilling scenario would be helpful.

A transition to a permafrost or glacial climate is expected to occur between 5 000 and 20 000 years AP. Major geological changes, such as groundwater flow and chemistry, rock movements will occur over these timescales but some estimates of the effects of these changes can be made. The range of potential environmental conditions, however, will be very wide and STUK considers that dose assessments would be largely meaningless for these timescales. Radiation protection criteria are therefore based on release rates of radionuclides from the geosphere to the biosphere. These criteria have been defined by STUK to be comparable with the effects of natural radionuclides and to ensure that large-scale effects are insignificant.

In the farthest future, quantitative safety assessments are not justified and are not required. Instead, bounding analyses and comparisons with natural analogues are appropriate. For example, the potential radiotoxicity of spent fuel becomes less than that in the natural uranium, from which the fuel was fabricated, and the hazard posed by the repository is comparable to that from a uranium ore deposit

In the discussion of this presentation, Esko Ruokola noted that the use of probabilistic approaches for uncertainty analyses was for the proponent to determine, although STUK considered stochastic approaches to account for variability (e.g., host-rock properties around emplacement holes) would be appropriate. He also emphasised that not all scenario results would be compared to the dose constraint (e.g., for the distribution of well cuttings).

Risk communication

An important step in the overall management of uncertainties is communicating the basis for the approach adopted to treat uncertainty and the reasons for decisions to other stakeholders. Other international programmes and discussion fora are actively considering the issues associated with risk and safety communication and the Workshop did not, therefore, address this topic in detail. Magnus Westerlind (SKI) did, however, give a plenary presentation on some of the results and conclusions from the RISCOM project.

Enhancing transparency and public participation in nuclear waste management

The RISCOM II project was conducted from 2000-2003 and was aimed at enhancing transparency in and public participation in nuclear waste management. It included both the development of a theoretical basis and practical tests and implementation through dialogue, development of a web site, interviews and hearings.

In RISCOM, transparency is regarded as the outcome of learning processes that increase all stakeholders perceptions of the issues. The RISCOM model of transparency is based on:

- Technical competence (are we doing things right?).
- Authenticity (are we doing what we say?).

- Legitimacy (are we doing the right things?).

Traditionally, performance assessment is an expert activity, but selection of a site gives rise to new "users" of Performance Assessment (PA), including municipalities, decision makers and members of the public. PA experts are therefore required to communicate, and this must included the assumptions and scenarios underlying analyses as well as the results.

The RISCOM project highlighted a number of questions concerning PA, notably what the relationship is between PA and EIA (Environmental Impact Assessment), and how and who should be involved in framing and conducting PAs. The conclusions reached were that it is important to communicate with stakeholders early, including the context of PA (why is it done), the scenarios assumed, and the criteria for judging performance. The focus should be kept on science, with PA communicated by experts, and clarification of factual and value-laden issues.

In the discussion, Magnus Westerlind stressed that communication and transparency were not necessarily concerned with reaching consensus. Rather, the process should improve understanding and improve the quality of decisions through awareness of values.

Uncertainty governance

The final plenary presentation before the Workshop separated into Working Groups described an approach to uncertainty management under development in Japan.

Uncertainty governance: An integrated framework for managing and communicating uncertainties

Hiroyuki Umeki (NUMO) described two approaches to uncertainty management or governance. In the first approach, uncertainty management in PA, different formalisms (e.g. probability theory, Bayesian theory, possibility theory, evidence theory) are integrated to provide a quantitative basis for models aimed at handling imperfect information. The second approach, uncertainty communication, establishes the concept of a network PA community in which members can use internet and other resources for PA.

The first approach is required because there are different types of uncertainty associated with radioactive waste management, and different approaches or formalisms are best suited to accounting for these. The approach advocated is intended to allow for a combination of these formalisms to be integrated within an assessment.

The second approach recognises the limitations of an assessment conducted by experts and viewed independently by users or stakeholders. The approach advocated is intended to allow collaboration between users and a synergy of expertise and thus increase understanding of the system and the uncertainties.

WORKING GROUPS

Working Group 1 – Risk Management and Decision making

Introduction

Within the overall context of the Workshop, Working Group 1 focused its discussion on two key objectives:

- to elaborate end-users' needs and preferences with respect to information and activities relating to risks and uncertainties in nuclear waste disposal;
- to clarify some of the concepts relating to the discussion on uncertainties and risk.

In particular, the group aimed to provide a bridge between those preparing safety case information and those using it for decision making or other purposes by looking at the type of information approaches that would best serve decision making.

The group aimed its discussion on (higher-level) decision makers, such as the public, politicians, administrators, and assessed various methodological approaches to decision making under uncertainty. The group noted that regulators should be considered as end-users of safety case information, but decided not to explicitly discuss regulatory needs since these were addressed by WG2.

Definitions of risk

From both the plenary presentations and the introductory presentations to the working group, it was apparent that there is some diversity of definitions with respect to terms such as "risk". The group acknowledged that the word "risk" could be interpreted as having different meanings for different end-users (nuclear power plant, waste, economics...), and compiled a set of characteristics for which alternative approaches or viewpoints exist.

- Objectivist/realist (regards risks as real) vs. constructionist (regards risk as a mental construct).
- Quantitative vs. qualitative.
- Different mathematical formulations:
  - probability times consequence;
  - expected (negative) utility;
  - open formulations.
- A description of risk requires consideration of:
  - a number of end states corresponding to various damages (e.g. deaths, contamination);
  - the sequences that leads to these end states, and
  - the associated probabilities.

- in particular, the dominant accident sequence and its full range of uncertainty and consequences.

- The probability of certain damage occurring (the damage can be different depending on the assessor (politician, technician, and economist).
- For technical experts, "risk" often means the product of probability and consequence. In public discussion risk may mean only the probability (of a negative consequence), although the consequences may be of most interest to the public.
- Both "constructed (perceived)" risk and "realist" risk do matter and the public may be concerned about both.

The group concluded that the difference between frequentist and epistemic interpretations of probability may be meaningful in some contexts but not of practical significance in other contexts. Similarly, most NPP or repository safety analyses are not purely objectivist, but include probabilities representing degrees of belief (e.g. where expert judgement is used).

Risk assessment and risk management

Following the discussion of "what is risk?", the group also discussed the terms risk assessment and risk management. Risk assessment was interpreted to be the evaluation and communication of risks, and may have a somewhat narrower focus than safety assessment. Risk management was interpreted as the whole sequence of risk assessment, decision making and consecutive actions that affect the realisation of the risk. In this context, it was suggested that there is a move away from risk-based decision making (i.e., based solely on the results of a risk assessment) to risk-informed decision making (i.e., other factors are taken into account as well).

The group noted two risk issues relating specifically to radioactive waste disposal facilities. The first was that the long time-frames considered in repository safety analyses may provoke additional questions as to the availability of meaningful risk estimates (can such estimates be scientific?) considering the uncertainties associated with the long timescales. The second was the extent to which risks can be affected or managed after decision making, which raises questions about the role and meaning of step-wise approaches, reversibility/retrievability and monitoring. There were different opinions expressed within the group on the role and value of these approaches and no consensus was reached.

The distinction between risk-based and risk-informed decision making is that a risk assessment is only one component of the latter. A key issue that also comes into play in risk-informed decision making is the concept of defence-in-depth versus risk reduction. In terms of repository systems, it then becomes important to determine whether the multi-barrier concept really consists of independent barriers, or if the design is based on risk reduction, with the barriers added or designs changed until a reasonable level of safety or compliance with regulations has been reached.

End-users of the risk information

The end users of risk information are those making decisions and who need the information to support this decision-making process. The group acknowledged that the risk information required depends greatly on the decision-making process, on the legal framework and cultural traditions. The group noted the variations between countries in decision-making processes, which may in turn affect the scope and conduct of risk assessments.

- **Finland**: decision-in-principle with local veto.

- **Sweden**: local veto, review of research, development and demonstration programme at 3-year intervals.
- **France**: three main options to be evaluated in 2006; scientific evaluation important; Parliament decision.
- **Hungary**: Policy of final disposal now, local veto, large compensation to municipalities/active information.
- **Japan**: No veto but voluntary approach.
- **USA**: Federal decision, court appeals.

Most radioactive waste programmes openly publish their information, but the amount of information produced can be very large. A key question raised by the group, therefore, was on how to deal with the potential conflicts between openness and transparency. Members of the group were more in favour of the management of information at different levels (providing "active" transparency), rather than unrestricted openness and drowning in information.

Additional questions relating to information release and decision making were discussed, in particular whether any effort is required to build the competence of decision makers to judge the proposals. Similarly, although transparency should allow access to the information at any level, is there a need to actively educate the public? This in turn raises questions about whether the public need, or want, to be involved, and at what level?

The group felt it was important to ensure that, at each level of information provided, decision makers should know the potential consequences relating to their decisions. It was also noted that politicians have the freedom not to accept information from the risk assessment – other values will always play a role in their decision making.

The term stakeholder is used extensively in discussions of risk management, but the group noted that there are different definitions for the term. For example, according to the terminology of NEA Forum on Stakeholder Confidence (FSC) it seems to mean anyone who has a role or interest in the project, whereas in the USA the decision maker is not a stakeholder in risk management at NPPs. According to the US definition, the scope of the term can also vary from step to step in the decision-making process – the regulator may be a stakeholder in governmental decisions but not in its own decisions. The group also noted that the word stakeholder may not have a direct translation in all languages.

Case studies: Finland and Sweden

To illustrate some of the issues relating to risk management and decision making in different countries, case studies from Finland and Sweden were presented to the working group. Similar lessons and experiences on the role of risk in decision making were noted in both cases:

- A clear definition of the problem and the (decision-making) process is critical.
- The possibility (or flexibility) of future modifications of the disposal concept is important.
- EIA (environmental impact assessment) should be considered as a valuable tool for public participation.
- Dialogues with an open agenda are preferred in order to let people present their questions. Preparation is required to ensure that answers can be provided. In particular, people want to understand how things work, and how it is possible to know about the future. They also

want waste organisations to show the process understanding and the role of science since these are important in building confidence.

- A consideration of alternatives to the proposed facility is viewed as important in supporting dialogue with stakeholders. As an example, in the Finnish Parliament the discussion focused on the comparison of alternatives instead of the issue of disposal safety.

Alternative risk methodologies

An approach complementary to the traditional probabilistic methods for risk assessment was presented by Georgy Bárdossy. This alternative mathematical methodology, in which vagueness is explicitly separated from randomness, has been applied in a case study of Hungarian sites/repository (e.g. the Püspökszilágy repository in Hungary).

The methodology described is based on the possibility theory and the theory of fuzzy sets, and includes a "phenomenological" classification of uncertainties (e.g. imprecision, vagueness, incompleteness, conflicting evidence....). The method applies less stringent rules than the standard probability theory and is particularly appropriate for assessing epistemic uncertainties and considering possibilities instead of probabilities.

The group acknowledged that the net benefits of this alternative mathematical approach merit further evaluation, perhaps through benchmarking, and an assessment, in particular, of their potential usefulness for the decision makers' needs. As the presentation was limited in time and the topic was new to most group members, the group was not in a position to reach a clear conclusion on the ability of the method to increase or decrease the transparency of risk information, on the one hand, and the complexity of the information, on the other hand.

The long history of development of probabilistic methods was considered as an advantage for the traditional approaches. A key task would therefore be to confirm, through additional applications or case studies, the potential added value of the new methods.

Best practice

The group discussed best practice for risk assessments that would provide useful information for end users. The group reached consensus on the following main components:

Any risk analysis must:

- describe the sequences of events;
- discuss the assumptions and basis of parameter choices;
- describe the end states;
- discuss the modality (possibility, probability, likelihood etc.), and
- incorporate expert peer reviews.

What may be different between risk analyses is the extent to which the use of probabilities is made explicit. A principal reason for such differences is the applicable regulations and the cultural context for these regulations. This is decisive in determining whether probability distributions are presented explicitly, but regardless of how regulations are written, the regulators always allow the waste management organisations to select the most appropriate means for presenting and communicating the safety case to both decision makers and laymen.

The group identified several other points for consideration in a risk analysis but did not reach a consensus as to their treatment:

- A fully deterministic safety case is not possible but does the quantification of probabilities increase transparency?
- Can/should scenarios be given probabilities – what would be the alternative?
- How is the defence-in-depth concept demonstrated?
- Do scenarios based on stepwise removal of barriers support a safety case?
- Are bounding calculations useful in a risk assessment?

General conclusions

The importance of stakeholder's involvement and end-user needs to be acknowledged, but stakeholders and decision makers are different in different countries so that decisions may have a different basis. Best practice in different countries will be affected by cultural traditions and the legal framework, although overall there is a common shift towards customer-oriented risk communication,

New methodological approaches have been proposed and are being tested but the group questioned whether the benefits justify the extra work and the potential increase in complexity of analyses and information to be presented.

Clarification of the concepts and terminology used in risk management would be useful. The group noted that it may be difficult to get consensus on universal definitions but stressed the benefit of organisations clearly presenting their definitions in comparison with international practices.

Concepts and activities such as retrievability and monitoring have been proposed as assurance measures, but the group did not reach a consensus on whether these represent feasible approaches to risk management following decision making. Further discussion of these topics would be of value.

Working Group 2 – Regulatory requirements and regulatory review of uncertainty and risk in safety cases

Introduction

Working Group 2 was concerned with the topic of regulatory requirements and regulatory review of uncertainty and risk in safety cases. Themes addressed included standard setting and determining appropriate regulatory end-points; the role of risk in regulations; and methods for evaluating risk assessments and other evaluations of uncertainty including the role of quantitative information and the importance of calculated risk in comparison to other lines of information.

Based on the plenary presentations and the topics addressed in the working group presentations, the group identified the following themes for discussion:

- Grouping of scenarios.
- Prescriptive vs. non-prescriptive regulations.
- Differences between risk-based and non risk-based regulation.
- Regulatory review of treatment of uncertainty in the safety case.
- Regulatory review of safety cases in which conservative and realistic assumptions are mixed.
- Risk dilution.

Grouping of scenarios

The Working Group was concerned specifically with the issue of how scenarios should be grouped with respect to their probability of occurrence, and how different classes of scenarios should be treated.

Countries with deterministic approaches commonly apply the following scenario groupings:

- reference scenario – based around the expected evolution of the system;
- less likely scenarios (altered evolutions);
- very unlikely scenarios (low probability);
- human intrusion – treated separately.

Regulatory criteria may vary for different classes of scenarios and it was noted that probabilistic approaches typically include the first and second categories in the overall system analysis. The development of understanding of the behaviour of the disposal system is facilitated by the use of 'what-if' scenarios, developed without reference to their probability of occurrence

The following broad conclusions were drawn:

- There is a need for systematic approach starting from a complete system description (systems approach) taking into account interaction (qualitatively) of Features, Events, Processes (FEPs).
- The normal evolution scenario represents the system evolution for expected external and internal conditions (climate etc). Other scenarios describe how other disturbances affect the evolution of the system.
- Categorisation and screening of scenarios can be based on:
  - likelihood of occurrence;
  - phenomenonological similarities (e.g. human intrusion, climate, initial defects);
  - sensitivity and bounding calculations.
- Screening arguments must be transparent.
- Definition of a limited set of representative envelope scenarios is appropriate.
- Regulators should take an interest in those scenarios that are excluded in safety cases, noting that disaggregation of one scenario into "sub scenarios" may cause that scenario to be excluded from consideration.

Prescriptive versus non-prescriptive regulations

It was noted at the outset that "regulations" usually have legal force and therefore represent mandatory requirements. Regulatory guidance is usually non-mandatory and may be general or detailed. Examples of this distinction include the United Kingdom, where safety principles and requirements are accompanied by general guidance, and in the United States, where there is prescription regarding many aspects of the assessment.

Some Working Group participants expected that regulatory guidance would tend to become more prescriptive as more experience is gained with safety assessment. Guidance currently under development in Germany was cited, where experience from previous regulations has fed into proposals for prescriptive guidance about selection of scenarios and how to determine what scenarios are regarded as less likely and unlikely. In other respects there was also evidence of regulations becoming less prescriptive, e.g. sub-system criteria are no longer required by regulators in the US.

Differences between risk-based and non risk-based regulation

Participants noted a gradual convergence of regulatory expectations, e.g. there are now similar expectations amongst regulators regarding supporting arguments, transparency and traceability, justification of assumptions and other qualitative aspects of treating uncertainties, whether the end-point is dose or risk.

Clearly, risk is one tool that can be used to quantify uncertainty; and risk-informed approaches can be more or less disaggregated; for example calculation and presentation of conditional risks for different scenarios. It was noted that there is no difference in parameter and scenario uncertainty in the mathematical sense, i.e. range of relevant parameter values can realistically be represented as a probabilistic distribution functions (pdfs).

A deterministic approach aims to segregate different elements of an assessment – consequence, frequency of occurrence, rather than attempting to aggregate them. But, it should also be noted that a deterministic approach does not exclude, for example, quantification of likelihood. An advantage of deterministic approaches is the avoidance of the problem of mixing widely different types of uncertainty (variability, incomplete knowledge, scenario probability). A disadvantage is that deterministic calculations rarely explore the full parameter space. Probabilistic approaches address this aspect by definition of parameter pdfs.

Regulatory review of treatment of uncertainty in safety cases

It is apparent that significant advances have occurred in recent years in terms of interactions between regulator and implementer ahead of the licensing process. It was noted that such interaction provides an opportunity for both sides to try to resolve their differences and reduce resources and time required for review of license application.

Examples of pre-licensing interactions noted by participants included:

- In the US – issues resolution process and associated integrated resolution status report (NRC).
- In Sweden – formal consultation process on siting and safety assessment issues and recurrent reviews of proponents RD&D programme.
- In France, Finland, Sweden, US, and UK – reviews of preliminary safety assessments.

It was also noted that the need to ensure that the independence of the regulator was not compromised has meant that national authorities have proceeded with great caution on this issue. A concern is that a perception of close interaction between a regulator and a developer could undermine public confidence in the regulatory process.

The Working Group discussed also the extent to which regulators need to develop their own assessment capability. It was felt that a fundamental requirement was that a regulator had a good understanding of the proposed disposal system and had sufficient knowledge to be able to identify what were the key issues in a safety assessment that should be independently reviewed. Participants noted that regulators should have the capability to disaggregate each element of judgement applied by the implementer and to assign to it an appropriate weight, i.e. there should be a focus on the basis for the results as well as on the results themselves. Pre-licensing interactions such as those in the UK and the US would tend to facilitate this process.

Clearly, regulators should be able to justify their decisions both to the implementer and to the public. It was noted that a range of approaches on this issue existed in different countries, depending on the extent to which regulators develop an independent safety assessment capability. In Germany the regulator is developing a capability which, in principle, would allow it to make an independent safety case.

Regulatory review of safety cases in which conservative and realistic assumptions are mixed

It was noted by participants that a mixture of conservative and realistic assumptions in a safety case is inevitable, and this is recognised by regulators. In those parts of the performance assessment where both types of assumptions are present, the assessment must err on the side of conservatism, but reviewers should be aware that this could obscure areas of uncertainty. Identifying what is a "conservative" assumption or approach may not be obvious. It may therefore be necessary for assessments to adopt realistic assumptions because of competing processes. In other words, what is conservative with respect to one process may not be conservative with respect to another competing process. Bounding analysis allows these issues to be better understood

Where "conservative" assumptions lead to results close to the regulatory criterion, there is still a need for supporting arguments and other demonstrations that uncertainties have been appropriately treated (e.g. the recent review of SFR facility by the Swedish regulators).

Risk dilution

Risk dilution is an issue for both risk based and non-risk based approaches. The concept of an annual risk criterion (which can be expressed as taking "the peak of the means") can lead to an apparent lowering of risk – risk dilution. One concern appears to be averaging the consequences of events with short duration but with uncertainty as to their time of occurrence. Using the "mean of the peaks" (also termed "total risk") is one way to get around this problem (although currently no regulations provide guidance on this issue). The use of the mean of the peaks is comparable to the use of a dose criterion, which gives the same level of protection for all individuals irrespectively when they are exposed. This is also compatible with the concept of sustainable development in that allows the exploitation of natural resources at any time. The mean of the peaks approach can, however, lead to misleading results by effectively combining results from events that are in fact independent. Some countries have therefore decided not to take this approach. The point was also made that Finland effectively allowed for some "risk dilution" by permitting time averaging of releases over a 1 000-year timescale for comparison with activity release constraints.

General conclusions

The group noted that there is ambiguity in the meaning of key terms and concepts and this led to difficulty in understanding the details of the approaches expected by regulators in different countries (e.g. deterministic vs. probabilistic approach; risk-based approach vs. non risk-based approach). Such ambiguity impedes good communication both in the technical community and amongst non-technical stakeholders.

For the purposes of the Working Group discussions the following definitions were used:

- **Risk-based approach**: "Regulatory decision making solely based on the numerical results of a risk assessment" (NRC definition).

- **Risk-informed approach**: "Risk insights are considered with other factors" (NRC definition).
- **Deterministic approach**: "The use of fixed values in modelling for characterisation of uncertainty" (working group definition).
- **Probabilistic approach**: "Characterisation of uncertainty with PDFs as input to modelling" (WG definition).
- **Risk**: "consequence*probability of occurrence" (WG definition).

The group concluded that development of a thesaurus to link definitions in regulations and guidance from different programmes would be of value.

It was also notable that the differences between approaches in different countries are not as great as was previously considered by the participants, i.e. there appears to have been a gradual convergence of different assessment approaches as programmes have matured. Examples of the evolving nature of regulations include the development of regulations in Switzerland and in Finland that combine dose and risk criteria for different sets of scenarios (Switzerland, Finland), and the development of site-specific (or context-specific) guidance in the US and in Finland.

Differences between "probabilistic" and "deterministic" approaches were discussed specifically. It should be noted that this is not the same as the differences between regulations with a dose criterion and those with a risk criterion, e.g. standards for Yucca Mountain require a probabilistic calculation of dose. Sweden has a risk criterion, but guidance does not yet prescribe any calculational approach. The Group concluded that the difference is strongly linked to the extent to which the regulator expects aggregation (probabilistic) vs. non-aggregation (deterministic) of consequence and likelihood.

It is clear that there are differences in the extent to which regulations prescribe the approach to be followed in assessments. Examples of this include regulations in the US that prescribe transport pathways, discharge area, characteristics of the RMEI etc. Also, proposed regulatory guidelines in Germany indicate how scenarios should be selected and categorised. In contrast to these approaches, UK guidance expects developer to take lead in proposing assessment approach.

The group concluded that a useful follow-up to the Workshop would be dialogue between regulators and other interested parties on the treatment of uncertainty and the role of risk. Such dialogue would ensure that the lessons learnt in one country can be transferred to others, and would help to avoid stakeholders' perceptions of differences between programmes from raising concerns.

Working Group 3 – Practical approaches and tools for the management of uncertainty

Introduction

The objective of the working group was to exchange experiences regarding the management of uncertainties in various national programmes, taking into account different regulatory frameworks. The discussion focused on the practical aspects of a safety case, and how different tools could or should be used when accounting for uncertainties. The following topics were addressed by the group:

1. Classifying and characterising uncertainties.
2. Determining the scope of uncertainty analyses and risk assessment.
3. Presenting uncertainty analyses and risk assessments.

These topics were then split up in more specific issues in order to focus the discussions. The conclusions that were agreed upon, as well as the points that were discussed and clarified but on which no consensus could be reached, are presented below.

Classifying and characterising uncertainties

Classification

There is a clear consensus among all national programmes on the importance of managing uncertainties in a safety case. In particular, it requires a clear classification since a large range of different uncertainties are to be handled. Though various classifications may exist, involving for example epistemic uncertainties vs. natural variability, randomness etc., the concept of *uncertainty classification* is both widely used and judged as necessary to perform analyses. The introductory talk by G. Bárdossy addressed this issue to some extent and questioned some of the approaches presently used in performance assessments. However, since it was recognised that other NEA activities have already dealt with this issue, it was not further elaborated during this working group session.

Aggregation/disaggregation

An important aspect in uncertainty classification and characterisation is *how uncertainties can be aggregated and* disaggregated in a useful way. As regards aggregation, it can be noted that there are different levels of aggregation. The higher level is the aggregation and characterisation of all possible evolutions, or of a large family of possible evolutions, into one assessment end-point, usually risk. Aggregation at a lower level can be those of scenarios, of situations in one scenario, etc, down to the aggregation of elementary phenomena.

Aggregation of situations into scenarios is judged to be useful when situations are comparable in terms of their effect on safety functions. There was no consensus on the use of aggregation of situations that are different in terms of effects on safety functions, except if this is required to prove regulatory compliance. The aggregation of various features, events and processes may help to evaluate their relative importance, or their possible interactions.

Generally, disaggregated analyses are necessary for detailed system understanding, for example when making design choices. They provide suitable guidance as regards design and research priorities. They are an important tool in order to account for possible parameter correlations in the calculations. It is generally recognised that such disaggregated analyses should be performed and presented in a safety case. Disaggregation is also necessary in the presentation of safety assessment results. However, one has to bear in mind that disaggregation is possible only to a level where data is available.

The appropriate level of disaggregation/aggregation needed in a particular programme depends on what the regulator requires, as well as on the goal of the assessment. It also depends on the nature of the system analysed. In all cases, an interaction between disaggregation and aggregation is required.

Characterising uncertainties

One important aspect of uncertainty characterisation is whether or not it is possible to attribute a probability (or a probability distribution) to them. Some uncertainties appear to be especially difficult to represent with probabilities, namely:

- Model/conceptual uncertainties, particularly when the model is aimed at representing a complex situation, involving multiple parameters and/or being heavily dependent on boundary conditions. For instance, various models describing climate evolutions/changes may coexist, and the relative probability of each may be difficult to assess.

- Changes in human behaviour are generally considered as unpredictable in the long term. That is why most national programmes demand that future human actions should be addressed without assuming major changes in the future. However, based on today's living conditions and social organisation, human actions can be associated with a probability. There were however diverging views within the Group as regards the relevance of using such current probabilities to represent long-term human behaviour.
- The probability of missing FEPs, or more generally the completeness of the analysis itself, cannot be described by a probability, although it can be considered as certain that no safety case is exhaustive.

A number of alternative approaches to handling uncertainties that can not be assigned probabilities are available. The robustness of the repository as regards their possible effects should be analysed and discussed. While emphasising the robustness of the repository against all types of uncertainties is generally advisable, it is particularly useful when addressing these particular types. The use of stylised assumptions that may compensate for a lack of knowledge is another possible approach. Most members of the group felt that guidance from regulators is helpful when employing such assumptions in a safety case, though no consensus was reached. The use of alternative models, to explore the effect of various choices, can also be envisioned. For compliance purposes, a conservative assumption may be chosen. Finally, even if no probability can be correctly justified, a probabilistic approach may however prove useful when exploring the sensitivity of a particular uncertainty.

Internal and external expert judgement plays an important role when characterising uncertainties. It is widely considered that a formal process should be organised with the expert to structure and systemise the interrogation as well as to achieve traceability. For example, a formal interrogation process may allow identifying and keeping track of assumptions or biases that might have been undetected or forgotten otherwise. When discussing models and parameters, correlations should be specifically addressed. Several national programmes, in particular the English (Nirex, 1998) and the French (Analyse phénoménologique des situations de stockage, Dossier 2001) one, have developed such systematic processes and have a positive feedback. However, based on such experiences, it appears that it may prove useful, under specific circumstances and after having completed the formal process, to allow for a less formal or more general description of the problem addressed, so that experts can express uncertainties that may not otherwise fit into the formalisms.

It is important to ask the "correct" questions in an elicitation process, and in particular avoid possible bias induced by the potential use of the data. This can be accomplished by asking the experts for expected parameter values and parameter ranges, rather than directly asking which value should be used in the assessment. Moreover, it is only useful to ask questions regarding measurable quantities. When dealing with highly uncertain topics, it may be difficult to account for the judgements of the experts and integrate them correctly in the assessment. Such cases, when an expert judgement cannot be formulated with enough accuracy, may lead to unrealistic assumptions in the assessment. It is then recommended that an iterative approach is used with the experts, verifying with them if their assumptions are correctly translated into the assessment and checking if they are in agreement with the results obtained.

Determining the scope of uncertainty analyses and risk assessment

Several members of the group stressed that *parameter correlations* are a potentially significant source of errors or misinterpretations when performing a safety assessment. For example, the solubility of radionuclides may be highly correlated to the chemical conditions of the surrounding environment, so uncertainties associated with both parameters should be dealt with in a common framework, as far as possible. Furthermore, to facilitate calculations, elicitations and system understanding, the system should be, to the extent possible, parameterised such that input parameters are independent. In the example above, this would ideally mean that the chemical conditions should be described by a set of parameters and that all relevant properties that depend on these conditions should be described as functional relationships to the parameters. As regards tools for identifying causes of correlations, FEP databases could be useful, possibly with a FEP elicitation process focusing on identifying correlations. However, no direct experience of a specific elicitation process dedicated to correlations was identified in national programmes. They are usually included in a more general parameter elicitation process.

Another difficult issue, and possible source of misinterpretations in safety/risk assessment, is that of *scenario probabilities*. Scenario probabilities are generally thought to be difficult to quantify except possibly for scenarios that are based on aleatory events, and it was noted that addressing the direct calculation of scenario probabilities is often avoided in national programmes. Three types of scenarios were identified, though this classification was not considered as necessarily exhaustive:

- "what if" scenarios and stylised or conventional scenarios, to which no probability can be assigned by definition;
- scenarios based on aleatory causes, to which probabilities or at least some judgement on their relative likelihood is usually accessible;
- scenarios based on epistemic uncertainties, such as an unexpected evolution of a parameter due to lack of knowledge, or the presence of an unidentified feature: a probability is much more difficult to associate to it, though it has been tried in some programmes (for example, by evaluating the probability of failure of a measurement tool).

It was reported about the ongoing efforts in Germany to develop regulatory guidance to classify scenarios of the second and third kind with regard to their likelihood of occurrence.

As regards tools for uncertainty analyses and risk assessments, it was agreed that currently used tools (such as deterministic methods and Monte Carlo methods) are fit for their purpose, i.e. evaluation of regulatory compliance and system understanding, and that no specific developments are urgently needed. However, other more innovative tools (such as fuzzy logic, possibilistic analyses and interval analyses as proposed e.g. by G. Bárdossy) have been used in some programmes, and could bring new ways to characterise and evaluate the importance of uncertainties. More experience is needed before it can be decided if these tools can bring new kinds of information into performance assessments, and if the possible complexity they add to the assessment is manageable and it matches the potential benefits. So, their use as complementary lines of argument should be encouraged. A possible way of addressing the issue would be as an international test case. Such a test case could also be used to explore ways of communicating results.

Presenting uncertainty analyses and risk assessments

Two practical aspects regarding the presentation of analysis results were specifically addressed: high consequence tails and risk dilution.

High consequence tails appear when presenting the distribution of results of a probabilistic calculation. It is first noted that not all high consequence tails have a real meaning in terms of safety analysis. Some are purely calculation artefacts, reflecting e.g. input distributions that are unrealistically broad or correlations that have not been properly treated. Care is thus needed when selecting input distribution functions before performing calculations. It is also necessary to check if correlations and epistemic uncertainties are as far as possible correctly accounted for. This can, as in the HMIP Dry Run 3 exercise (HMIP, 1992) be done by means of a "high-risk re-analysis". If a high consequence tail persists, then it must be discussed qualitatively. This usually poses less problems when regulations are expressed in terms of acceptable risk, or levels of confidence, as compared to the case when the regulations refer to an acceptable threshold.

Risk dilution was recognised as an unavoidable consequence of some combinations of systems analysed and applicable regulations. In particular, dilution may appear when a system involves a release of radionuclides over a short period of time or a limited space and when the acceptable threshold is expressed in terms of risk. In the ongoing revision of Safety Criteria in Germany, this potential for risk dilution was amongst the reasons for withdrawing from the originally envisaged risk criterion. Regulators need to be aware that such a danger of risk dilution exists, and possibly provide guidance as to how to apply regulations in the context of possible risk dilution. Implementers need to explore such effects as thoroughly as possible, and a useful approach to illustrate the effect of risk dilution could be to compare the mean of the peak consequences and the peak of the mean consequences.

In the discussion it was suggested the term "risk dilution" should be replaced by "risk dispersion", since this would better reflect the fact that risk is not decreased but "spread".

In conclusion, it can be stated that a very wide range of approaches and practical tools have been experimented within national programmes. Sharing experiences and confronting possible problems was found to be a positive experience. A tool may be more or less suitable depending on the specific regulatory context and the objectives of a particular national programme at a particular stage of maturation. Having access to a wider variety of tools, even if these must be used with the appropriate precautions, may allow for improvements in the management of uncertainties, and is therefore judged to be in general positive.

GENERAL DISCUSSION

As a prelude to the final discussion, Steve Hora summarised his impressions of the Workshop, the issues raised and the current status of risk assessment and uncertainty management in safety cases for radioactive waste management facilities.

Personal reflections on workshop by Steve Hora

Steve Hora noted that although many things had changed over the preceding five years or so, one thing that has remained constant is that the issues dealt with by this Workshop are extremely difficult. Risk and performance assessment for nuclear waste must be one of the most daunting efforts of its kind as the time spans involved, the complexity of the processes, and the costs and potential consequences are truly unique.

Steve Hora noted that the risk triple (scenario, consequence, probability) was a good starting point for his reflections. During the past decade the FEPs approach (features, events, and processes) has been adopted for the construction of scenarios. Although this approach aims to provide completeness there always seem to be significant new scenarios that arise later in the analysis. This means that uncertainties must not only account for "what we know" and "what we know we do not know", but also for "what we do not know we do not know". These final uncertainties can be very large.

With respect to the second element of the Kaplan-Garrick triple, consequence, Steve Hora expressed some concern about the end points that are being proposed as criteria for licensing. He noted that the concept of a reasonably maximally exposed individual is somewhat stylised, and that increases in cancers or years lost to premature death may be appropriate criteria. He noted that there had been discussion throughout the Workshop of risk dilution, and that this area of concern appears to be directly related to the criteria employed.

Probability is the most controversial of the three elements of risk. Steve Hora noted that there had been discussion of aleatory versus epistemic probability, but that there is a bias against epistemic probabilities of human actions and events – a bias to avoid using them. He considered that this may be due to the dominance of physical scientists in the performance assessment process. Social scientists can tell us a lot about human behaviour and they should be engaged in the performance assessment process.

The need to address issues through probabilities extends to the debate about deterministic and probabilistic analyses. Steve Hora noted that there seems to have been some movement in both camps. Those who have proposed TSPA (total systems performance assessment) now seem more content with probabilistic analyses of distinct scenarios (e.g., setting apart human intrusion or volcanism). The determinists on the other hand, are grouping scenarios into categories labelled *likely, unlikely*, and *very unlikely* or *reasonable* and *unreasonable*, which sound a lot like probability.

One of the difficulties that distinguishes risk analysis of radioactive waste disposal from other risk analyses is the enormous time spans involved. Steve Hora noted that it may be tempting to avoid these problems by shortening the time frame for analysis or substituting stylised representations of the future (e.g., assuming a constant biosphere and geosphere), but that such shortcuts would not set well with the public. He argued that the problem must be confronted and that assessments must acknowledge the fact that the problem at hand simply will not admit a "tight" solution.

Steve Hora noted the attention paid at the Workshop to risk communication and public opinion. This is a new development that he considered would be of great benefit to the participant countries.

Final discussion

Following Steve Hora's reflections, there was a period of general discussion about the issues raised throughout the Workshop.

This discussion noted in particular that, as well as providing an opportunity for participants to discuss some of the differences between approaches, the Workshop had highlighted the fact that there are important similarities between countries and approaches. These relate to the importance that is now attached to transparency and traceability in the information presented to decision makers and stakeholders, and to the regulatory focus on the basis for the results (risk-informed) as well as the results themselves (risk-based).

CONCLUSIONS

The Workshop addressed a wide range of topics relating to the management of uncertainty in safety cases, and there was extensive discussion, particularly within the Working Groups, of different approaches used in different countries and programmes. These discussions led to the following observations and conclusions and also highlighted potential areas for further work.

Regulatory approaches

- There is no simple distinction to be made between regulations with risk or dose criteria.

  In particular, regulations requiring the calculation of dose for the normal or expected evolution may require an assessment of risk for less likely scenarios. Also, regulatory guidance requiring the calculation of risk for natural events and processes may not require assessment of probabilities of human intrusion scenarios.

- Regulators have similar expectations regarding the importance of treating uncertainty whatever the regulatory end-point.

  Expectations regarding the evaluation and presentation of uncertainties do vary depending on the end-point used. There are, however, similar expectations regarding the use of supporting arguments, transparency and traceability, justification of assumptions and other qualitative aspects of treating uncertainties, whether the end-point is dose or risk.

- Regulators see interactions with implementers ahead of the licensing process as an opportunity to identify critical issues, to resolve differences in approach and to reduce the resources and time required for review of a license application.

- Overall, regulatory expectations are for safety cases that are risk-informed rather than risk-based.

Assessment of uncertainty and risk

- All assessments must address the components of the risk triplet: What can happen? What are the consequences? And what is the likelihood? Approaches differ in the extent to which probabilities are assigned explicitly (e.g., as probability density functions) or implicitly (e.g., through the selection of likely and less likely scenarios).

  The explicit use of probabilities to characterise uncertainty is not restricted to calculations of risk. Overall, there is a role for deterministic and probabilistic calculations in both risk and non-risk oriented assessments.

- A key difference between different approaches to the treatment of uncertainty is the extent to which uncertainties are aggregated or disaggregated.

  Disaggregated analyses are of value for developing detailed system understanding and providing information for design choices and research priorities. Aggregated analyses may be of value in assessing scenarios that have a similar effect on safety functions, and are required under some regulatory approaches.

- All types of uncertainty assessment require the use of expert judgements. There was consensus as to the need for a formal process for documenting and using such judgements.

- Risk dilution, or risk dispersion, is recognised as a potential issue in some assessments depending on the methodology used and on the regulatory context.

  There is no simple mathematical solution to this issue, which is related in part to regulatory philosophy as to who should be protected and the definition of the exposed group. The overall consensus was that the proponent should explore potential risk dilution effects, and that regulators need to be aware of such effects and consider developing guidance as to acceptable approaches.

Risk management and decision making

- The decision-making process differs between countries, reflecting different legal frameworks and cultural traditions. Stakeholders in decision making also differ between countries. In all cases, early dialogue, together with transparency and openness, are recognised as important.

- Different end-users of information from a safety case may attach different meanings to the term risk. Results of risk assessments should therefore be set in a broad perspective so as to inform as wide a range of end-users as possible.

- Risk assessment is the initial stage of a sequence that also includes decision making and risk management. In the context of radioactive waste disposal facilities, the extent to which risks can be affected after repository closure is debatable.

  Potential risk management approaches include step-wise decision making, reversibility/ retrievability and monitoring. No consensus was reached as to the role of these approaches, but it was concluded that an iterative coupling of risk assessment and risk management options would be of value.

Recommendations and potential future work

- The Workshop recommended the continuation of international dialogue between regulators and implementers in the area of uncertainty and risk management, to further explore alternative regulatory approaches and to share experiences with different assessment tools and approaches.[2]

  The Workshop concluded that risk assessment methodologies for disposal facilities were converging as programmes matured, but that continued dialogue would help in developing an understanding of the different approaches, with their associated strengths and drawbacks. Such an understanding would also help to provide assurance to stakeholders and decision makers that any particular approach was fit-for-purpose.

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2. Since the Workshop, the NEA, EC and individual regulators have taken initiatives aiming at a systematic review of regulatory approaches. To avoid overlap these initiatives should be considered in the discussion of potential future IGSC activities.

Throughout the Workshop, it was apparent that different terminologies are in use in different assessments, and that different meanings are attached to the concept of risk by different stakeholders. As a consequence, the Workshop concluded that a thesaurus linking definitions and terminologies in different programmes would be of value. Such a thesaurus could provide assurance to stakeholders concerned at apparent differences, as well as promote understanding between programmes.

- The Workshop recognised the importance of risk management in an iterative cycle of safety assessments. Further discussion of the relationship between iterative risk assessment and risk management is a candidate for further NEA initiatives.

- A safety case will likely include multiple safety arguments. The relationship between different arguments, and regulatory approaches to their review and evaluation, are candidates for further NEA initiatives.

REFERENCES

HMIP (1992), Dry Run 3: A Trial Assessment of Underground Disposal of Radioactive Wastes Based on Probabilistic Risk Analysis, Overview. Department of Environment: Her Majesty's Inspectorate of Pollution-Commissioned Research DoE/HMIP/RR/92.039, June 1992, United Kingdom.

Nirex (1998), *Overview of the FEP Analysis Approach to Model Development*, Nirex Science Report S/98/009.

NEA (1997a), *Disposal of Radioactive Waste. The Probabilistic System Assessment Group: History and Achievements, 1985-1994*, OECD, Paris.

NEA (1997b), *Disposal of Radioactive Waste*: *Lessons Learnt from Ten Performance Assessment Studies*, OECD, Paris.

NEA (1999), *Confidence in the Long-term Safety of Deep Geological Repositories: Its Development and Communication*, OECD, Paris.

NEA (2002a), *Establishing and Communicating Confidence in the Safety of Deep Geologic Disposal*, OECD, Paris.

NEA (2002b), *The Handling of Timescales in Assessing Post-closure Safety of Deep Geological Disposal, Workshop Proceedings*, *Paris, France, 16-18 April 2002*, OECD, Paris.

NEA (2004), *The Post-Closure Safety Case for Geological Repositories*. *Nature and Purpose*, OECD, Paris.

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PLENARY SESSION

RISK IN TECHNICAL AND SCIENTIFIC STUDIES: GENERAL INTRODUCTION TO UNCERTAINTY MANAGEMENT AND THE CONCEPT OF RISK

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The management of uncertainty has always been of concern to nuclear reactor designers and regulators. Before Probabilistic Safety Assessment (PSA), uncertainties in the frequencies of accidents could not be quantified and the nuclear community developed the concept of defense-in-depth to assure that these frequencies were very low. After PSA (roughly, after 1975), some of the frequencies could be quantified and, in addition, the major accident sequences could be identified.

A comparison of the pre-PSA and post-PSA thinking provides useful insights regarding the value of the systems approach that PSA takes. Before PSA, the situation was as follows:

1. The core damage frequency (CDF) was not quantified but was thought to be very low.
2. The accident consequences were thought to be disastrous [1]. To keep a very low CDF, a precautionary attitude prevailed leading to:
   i) Conservatives designs and operations.
   ii) The defense-in-depth philosophy.
   iii) Large safety margins.

Defense in depth was the cornerstone of the safety philosophy. It was formally defined much later (in 1999) by the US Nuclear Regulatory Commission (USNRC) as: “Defense-in-Depth is an element of the Nuclear Regulatory Commission’s safety philosophy that employs successive compensatory measures to prevent accidents or mitigate damage if a malfunction, accident, or naturally caused event occurs at a nuclear facility.”

The publication of the Reactor Safety Study (RSS) in 1975 and subsequent PSAs performed worldwide changed the approach to safety. The plants were analysed as integrated socio-technical systems. This new approach revealed that:

1. There were important contributors to risk (e.g., interfacing systems LOCA) that were previously unknown.
2. CDF estimates were higher than previously believed.
3. Accident consequences were significantly smaller.
4. Many regulatory requirements that had been imposed in the name of defense-in-depth did not contribute significantly to safety.

This comparison leads to the following insights:

1. Beliefs based on "deterministic" analyses without a risk assessment can be wrong.
2. Precautionary (defense-in-depth) measures are not always conservative – some important failure modes were missed.
3. In some instances, unnecessary regulatory burden was imposed on the licensees wasting valuable resources.

Since PSA provides quantitative estimates of accident frequencies, both industry and regulators have focused on the uncertainties in these estimates. A systematic way to deal with these uncertainties is provided by the subjectivistic theory of probability [2]. The application of this theory to PSA proceeds as follows [3] [4]: The "model of the world" (MOW) is the mathematical model that is constructed for the physical situation of interest, such as the occurrence and impact on a system of a physical phenomenon. The "world" is defined as "the object about which the person is concerned [5]." There are two types of models of the world: deterministic and probabilistic. Examples of deterministic MOWs are the various mechanistic codes that we use, e.g., thermal-hydraulic codes. However, many important phenomena cannot be modelled by deterministic expressions. For example, the occurrences of earthquakes exhibit variability that we cannot eliminate; it is impossible for us to predict when the next earthquake will occur. We, then, construct models of the world that include this uncertainty. A simple example is the Poisson model for the probability of occurrence of k events in a period of time (0, t), i.e.

$$\Pr[k / \lambda, H] = \frac{e^{-\lambda t}(\lambda t)^k}{k\,!}, \quad k = 0, 1, 2, ... \qquad (1)$$

The argument of this expression shows explicitly that this probability is conditional on our knowing the numerical value of a parameter, namely, the occurrence rate λ, as well as on our accepting the assumption H = {the times between successive events are independent}. As with all probabilities, it is understood that this probability is also conditional on the totality of our knowledge and experience.The uncertainty described by the model of the world is sometimes referred to as "randomness," or "stochastic uncertainty." Because these terms are used in other contexts also, these models have recently been called *aleatory* models.

As stated above, each model of the world is conditional on the validity of its assumptions, H, and on the numerical values of its parameters, e.g. λ. Since there may be uncertainty associated with these conditions, we introduce the *epistemic* probability model, which represents our knowledge regarding the numerical values of the parameters and the validity of the model assumptions. Uncertainties in assumptions are usually handled via sensitivity analyses or by eliciting expert opinions. Parameter uncertainties are reflected on appropriate probability distributions. For example, for the Poisson rate: $\pi(\lambda)d\lambda$ = Pr (the rate has a value in dλ about λ). We note that the distinction between aleatory and epistemic uncertainties is introduced for modelling purposes and communication. This distinction is not always clear in practice. Conceptually, there is no difference (there is only one interpretation of probability, that of degree-of-belief) [6].

PSA is a scenario-based approach. It is useful to think of it as a set of triplets [7]:

$$R = \{< s_i, \pi_i(\varphi_i), c_i >\} \qquad (2)$$

where

s_i: scenario i, i = 1,…,N

φ_i: frequency of s_i (aleatory uncertainty)

π_i: probability density function (pdf) of φ_i (epistemic uncertainty)

c_i : consequence i

All modern PSAs for technological systems identify scenarios and rank them according to their frequencies.

Equation (2) can be the basis for a discussion on uncertainties by asking the following questions:

- Is the scenario list complete? (Incompleteness uncertainty).
- Are the models in the scenarios accepted as being reasonable? (Model uncertainty).
- Are the epistemic pdfs of the scenario frequencies representative of the current state of knowledge of the community? (Parameter uncertainty).

As stated above, uncertainties in assumptions are usually handled via sensitivity analyses or by eliciting expert opinions [8] [9]. Since the PSAs are usually performed to help a government agency to make decisions, they should represent the views of the wider expert community and not just the experts who were involved in the study.

The consequences of these uncertainties are:

1. Decision making must be risk-informed, not risk-based.
2. Traditional safety methods, such as defense-in-depth, have a role to play.
3. It is difficult to assess how much defense-in-depth is sufficient.

Regarding defense-in-depth (DID), two interpretations have been proposed [10]. The structuralist interpretation asserts that DID is embodied in the structure of regulations and in the design of the facilities built to comply with those regulations. The designers continually ask the question: "What if this barrier or safety feature fails?" The rationalist interpretation asserts that DID is the aggregate of provisions made to compensate for uncertainty in our knowledge of accident initiation and progression. They both deal with uncertainty; however, the structuralist does not need a PSA, while the rationalist does.

Both interpretations have weaknesses. Arbitrary appeals to the structuralist interpretation of defense-in-depth might diminish the benefits of risk-informed regulation, such as the avoidance of unnecessary regulations. On the other hand, strict implementation of risk-informed regulation (the rationalist interpretation of DID) without appropriate consideration of the structuralist defense-in-depth could undermine the historical benefits, i.e., protection against unexpected events. The structuralist interpretation is more appropriate when large uncertainties due to scenario incompleteness and model inadequacy are present.

Reference 10 proposes a "pragmatic" approach, i.e., apply defense-in-depth (the structuralist approach) at a high level, and implement the rationalist approach at lower levels, except when PSA models are incomplete, in which case one should revert to the structuralist approach.

The USNRC is now risk-informing its regulations [11]. Risk-informed decisions use epistemic mean values from the PSA to compare with various goals. When the mean value of a risk metric approaches the goal, the USNRC staff warns that there will be "increased management attention," which means that the analysis will undergo significant scrutiny.

Although the appropriate framework for analysing uncertainties is in place, formal guidance as to how these uncertainties should be taken into account in risk-informed decision making is not available at this time.

References

[1] Beckjord, E.S., M.C. Cunningham and J.A. Murphy (1993), "Probabilistic Safety Assessment Development in the United States 1972-1990," *Reliability Engineering and System Safety*, 39 pp. 159-170.

[2] De Finetti B (1974), *Theory of Probability,* Vols. 1 and 2, Wiley, New York.

[3] Apostolakis G. (1990), "The Concept of Probability in Safety Assessments of Technological Systems," *Science*, 250, pp. 1359-1364.

[4] Apostolakis G.E. (1994), "A Commentary on Model Uncertainty," in: *Proceedings of Workshop on Model Uncertainty: Its Characterization and Quantification*, Report NUREG/CP-0138, US Nuclear Regulatory Commission, Washington, DC.

[5] Savage L.J. (1972), *The Foundations of Statistics,* Dover Publications, New York.

[6] Winkler R.L. (1996), "Uncertainty in Probabilistic Risk Assessment," *Reliability Engineering and System Safety,* 54, pp. 127.

[7] Kaplan S. and B.J. Garrick (1981), "On the Quantitative Definition of Risk," *Risk Analysis* 1, p. 11.

[8] Budnitz R.J., G. Apostolakis, D.M. Boore, L.S. Cluff, K.J. Coppersmith, C.A. Cornell, and P.A. Morris (1998), "Use of Technical Expert Panels: Applications to Probabilistic Seismic Hazard Analysis," *Risk Analysis*, 18, pp. 463-469.

[9] Zio E. and G.E. Apostolakis (1996), "Two Methods for the Structured Assessment of Model Uncertainty by Experts in Performance Assessments of Radioactive Waste Repositories," *Reliability Engineering and System Safety*, 54, pp. 225-241.

[10] Sorensen J.N., G.E. Apostolakis, T.S. Kress, and D.A. Powers (1999), "On the Role of Defense-in-Depth in Risk-Informed Regulation," *Proceedings of PSA '99, International Topical Meeting on Probabilistic Safety Assessment*, pp. 408-413, Washington, DC, August 22-26, American Nuclear Society, La Grange Park, Illinois.

[11] Caruso M.A., M.C. Cheok, M.A. Cunningham, G.M. Holahan, T.L. King, G.W. Parry, A.M. Ramey-Smith, M.P. Rubin and A.C. Thadani (1998), "An Approach for using Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis," Reliability Engineering and System Safety, 63, pp. 231-242 (also known as Regulatory Guide 1.174).

RISK PERCEPTION AS A FACTOR IN POLICY AND DECISION MAKING

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Abstract

Risk perception is often believed to be an important factor in policy decision making, when it comes to the management of hazardous technology. Research on risk perception by the public since the 1970s has purportedly shown that such perception is emotional and based on ignorance. Experts, on the other hand, have been claimed to be objective and correct in their risk assessments. The present paper reviews a large body of research which has led to a quite different conclusions, viz. that emotions play only a marginal role in risk perception, which is mainly driven by ideological concerns and attitudes. The methodological shortcomings of the prevailing view of risk perception as emotional and simply misinformed are described.

Key words: risk perception, risk management, hazardous technology, attitude, emotion

Policy making in matters associated with risk is often difficult. The siting of nuclear waste repositories is one of the most dramatic examples. In many countries, such siting has run into what seems like almost intractable difficulties, due to local or national opposition. More generally, political decisions in matters of risk tend to be overly responsive to what is believed to be the public demands, resulting in skew allocations of resources to various safety programs [1-4]. This is so in spite of indications that people do not really demand, or accept, very skew resource allocations [5]. Politicians have, however, at times erroneous views of the public's beliefs and attitudes regarding risk [6].

Why should risk be important? We have repeatedly found risks to be more important than benefits [7, 8]. In related work, we found that people are more easily sensitised to risk than to safety [9]. Mood states have been found to be more influenced by negative expectations (risk) than by positive ones [10]. Tversky and Kahneman's Prospect Theory of decision making posits that monetary losses are more abhorred than corresponding gains are desired [11]. People seem to be more eager to avoid risks than to pursue chances.

In the case of nuclear waste, arguments voiced against proposed repository siting tend to center on risk, especially health risks of ionising radiation [9, 12, 13]. Such health concerns cannot be met with economic arguments about new jobs or other types of economic compensation, at least not in all cultures and countries where the problem arises. However, some studies have found that the most affected sub-populations, those living closest to a proposed site, may be positive while those living in the same larger region are negative [14]. It is possible that such differences reflect the effects of economic factors, as well as – in some cases – familiarity with nuclear facilities and job experience in the nuclear industry [8].

The opposition to a siting project may take different routes to exert political influence on the process. Regional opposition, as reflected for example in state level decisions in the USA, may be very strong in spite of local up-backing of a project. At the national level, we see in Sweden that politicians currently assume a very low profile, arguing that the matter is for local authorities to decide [15]. This is, of course, only part of the truth because a possibility of over-ruling a local veto exists, as a final measure [16-18].

In addition, the whole siting issue is intimately connected to national energy policy. It remains to be seen how national policy will be developed in the coming years, when some very hard decisions have to be taken. Earlier experience, from the 1970s, shows that many voters were likely to change their traditional political preferences on the basis of energy policy options. The political situation was de-stabilised due to the nuclear power controversy, resulting in a change of government in 1976, the break-up of a coalition government in 1978 and a nuclear referendum in 1980, following the TMI accident in the USA. Temporary opinion changes have later been observed, and new political turbulence has resulted, such as the events following the Chernobyl accident in 1986 [19]. Much of contemporary political thinking seems to be governed by the belief that a new nuclear disaster, somewhere in the world, will lead to new political demands for the fast phasing out of nuclear power.

Research basis of policy beliefs

Hence, policy making in matters of risk and hazard is very hard and it is to some extent governed by beliefs about the public's fear and volatility of beliefs, driven by such external events as foreign nuclear accidents and disasters. These political beliefs have been backed up by social and behavioural research on the public's risk perception, carried out mainly in the USA, since the end of the 1970's. There are two major approaches, called Cultural Theory of Risk Perception, and the Psychometric Paradigm.

In 1982, Mary Douglas and Aaron Wildavsky published their book "Risk and Culture" [20], where they suggested a complicated theory of risk perception, termed the Cultural Theory of Risk Perception. Briefly, it amounted to a typology where people were regarded as egalitarians, individualists, hierarchists and fatalists. Membership in any of these categories was socially functional. These groups were said to "choose" different hazards to be concerned about, suggesting that risk beliefs were little reality oriented, and mostly socially motivated. Empirical data published by Wildavsky and Dake seemed to support the theory [21].

The theoretical background and formulation of Cultural Theory was criticised by Boholm [22]. Empirical work on the theory was critically assessed by Sjöberg [23]. Although culture is a broad concept covering important factors, the work by Douglas and Wildavsky treats culture only in a very limited, speculative and highly restrained manner. Later work by anthropologists such as Åsa Boholm [24, 25] is more promising but has not yet reached a stage where more definite statements can be made.

More extensive work on risk perception was carried out by an American group led by Baruch Fischhoff and Paul Slovic, both of them psychologists. This work is often summarised under the heading "The Psychometric Paradigm". Fischhoff and Slovic claimed that "dread" is the main factor driving attitudes to hazardous technology such as the nuclear one [26-29]. Another important factor according to them was novelty of a risk, and ignorance of it. A two-dimensional system (Dread vs. New Risk) was used to describe a large number of hazards, and nuclear technology was found to be extreme in both respects: highly dreaded and new and unknown. Parallel to this work, social trust has been claimed to be another important determinant of perceived risk [30].

In the original work, and much of the later one as well, no risk target was specified. It is clear, however, that risks are judged differently when pertaining to one's own person (personal risk) or to others (general risk). In most cases, personal risk is judged as smaller than general risk, a finding related to the unrealistic optimism affecting health related beliefs, as documented by Weinstein [31, 32]. The two types of risk also have different correlates, general risk being related to policy attitudes especially for lifestyle hazards (smoking, drinking alcohol, etc). When no target is specified, people seem to judge general rather than personal risks [33, 34].

Slovic and other researchers went on to formulate, in the 1980's, a "stigma theory" which posits that hazardous facilities create a stigma of an area, leading to loss of economic opportunities and also to people living there being ostracised in the wider society [35]. The most recent work in the Psychometric Paradigm claims that "affect" is important in driving perceived risk [36, 37].

Experts have also been investigated, to a limited extent [38, 39]. On the basis of a very small sample of risk analysts (N=12), it was concluded that experts make "objective" risk judgments, unaffected by factors which were found to be important in the case of the public (dread, novelty). This early work was critically assessed only recently [40, 41]. Apart from the sample being very small, the studied risk analysts could not have had expertise in the many and very varied topics investigated, from nuclear power plants to mountain climbing. In this work, it seemed that experts made correct risk judgments, and that they were not affected by such factors as emotions or ignorance.

Summing up, risk perception work appeared to imply that the public reacts emotionally, and out of ignorance, with regard to their risk perceptions. Experts are, in contrast to the public, objective and correct in their risk perceptions, which are not contaminated by emotions and other biasing factors. Trust in experts could re-establish the gap between the experts and the public, trust being a very important factor in perceived risk.

This work has enjoyed a wide-spread credibility, in spite of serious weaknesses which I now briefly review.

Assessment of the prevailing views of risk perception

Nine critical points will be made here:

1. The models proposed seemed to be very powerful in accounting for perceived risk and risk acceptance, but that was an illusion, based on misleading data analysis [42]. Mean values were used in regression analyses. When raw data and individual differences were analysed, amount of explained variance dropped from about 80 to 20 percent [43]. Considerable improvement has been achieved by introducing new factors in the original model, such as Interfering with Nature [44]. Another important factor, related to Interfering with Nature, is that of moral value [45]. Man-made disasters are reacted to very differently from natural disasters, in part because there is nobody to blame for natural disasters.

2. The original work on "dread" did not measure only emotion, but mainly judgments of the severity of consequences of an accident [46]. The dread item has turned out to have less explanatory value than the items measuring severity of consequences. Only recently, more emotion items have been introduced in the models [47].

3. The notion that "new risk" is very important in accounting for perceived risk has not been supported in current research [48, 49]. Novelty of a risk is a very marginal factor in risk perception. Besides, nuclear technology is hardly a new technology to-day, as it may have

seemed to be in the 1970's when the notion of novelty as a factor in risk perception was introduced.

4. "Stigma" has never been established as a factor, except as a *post hoc* explanation of a few cases. Stigma theory cannot be used to predict events, nor can it explain the large prevalence of non-stigma cases (the vast majority with regard to nuclear facilities) [50, 51].

5. Current beliefs that "affect" (emotion) is an important factor in risk perception are mainly based on the fact, well known in other literature [52, 53], that attitude tends to be strongly correlated with perceived risk. Researchers within the Psychometric Paradigm chose to use the word affect for what is more appropriately called attitude, thus giving rise to the erroneous belief that they had shown that emotions influenced risk perceptions [54].

6. The belief that risk policy attitudes are based on perceived risk misses at least two important qualifications. First, policy attitudes are based on perceived or expected consequences of e.g. an accident, not its risk (which is mainly interpreted as probability) [55, 56]. Probability tends to be ignored [57]. Second, attitude to a technology is largely based on beliefs regarding its benefits and whether it is indispensable or not, if viable alternatives exist [46, 58].

7. Social trust is fairly marginal when it comes to accounting for perceived risk [59, 60]. Trust in the value of science is more important. People may well think that experts are honest and competent, yet that their scientific basis is insufficiently well developed [61, 62], as Drottz-Sjöberg found in her work on attitudes, following the two local repository referenda that have been held in Sweden. More research is needed, in the eyes of many, or they even reject the value of science and opt for other notions of knowledge, such as those offered by New Age proponents. In studies especially oriented towards New Age beliefs and world views, it was found that such beliefs account for some 10-15 percent of the variance of risk perception [63, 64].

8. While experts tend to give lower risks estimates than the public, in their own area of expertise and responsibility, the structure of their risk perceptions is similar to that of the public's [41].

9. Cultural theory has failed to account for more than a tiny fraction of the variance of perceived risk [23, 64]. Small correlations between perceived risk and dimensions of Cultural Theory around 0.10 were termed "strong" by some researchers [65], but the explanatory power is just a few percent of the variance of perceived risk. The fact that there may be a practical use to some independent variables with such weak relationships to criteria, does not imply that they are useful in theoretical work [64].

Conclusion

Misconceptions based on the psychometric paradigm have indeed penetrated very far. Jasanoff [66] put the matter quite well in the following citation:

> *"The psychometric paradigm, in particular, has been instrumental in preserving a sharp dualism between lay and expert perceptions of risk, together with an asymmetrical emphasis on investigating and correcting distortions in lay people's assessments of environmental and health hazards. In policy settings, psychometric research has provided the scientific basis for a realist model of decision making that seeks to insulate*

supposedly rational expert judgments from contamination by irrational public fears". (p. 98).

The simple diagram, reproduced many times (see e.g. Slovic [27]), of the factors Dread and Novelty, seemed to show convincingly that people oppose nuclear power because they were emotional and ignorant. And, as Jasanoff points out, experts were widely held to be rational and objective in their risk perceptions. The widespread notion that policy decisions should ignore the public's perceived risk probably has some of its roots or at least considerable support in these conclusions from the psychometric model. It disregards the simple fact that the views of the public cannot and should not be ignored in a democracy [67, 68].

In our research, briefly summarised above, we have found a quite different picture of the risk perceiver, be he or she an expert or not. The dominating factors in risk perception are of an ideological character, such as attitude or beliefs that a technology is interfering with Nature. Three points need to be stressed in particular:

- Attitude is a very important factor. In the case of nuclear risk, attitude to nuclear technology is an important explanatory construct.
- Moral issues, intimately connected with notions about Nature, account for a large share of risk perceptions and attitudes.
- Trust in science emerges as a factor of great importance. The belief that the development of technology involves unknown dangers is very important, and it seems no less rational than not believing that such is the case. Science does develop all the time and risks we do not know about today will be discovered tomorrow. If experts say "there is no risk" this usually means "no risks have yet been discovered".

The dualism pointed to by Jasan off in the citation above takes on a very different meaning in the light of these new research results. The driving factor behind risk perceptions and attitudes is not emotion, nor is it ignorance, but ideology and related epistemological beliefs. Risk managers and risk communicators may become more successful than hitherto, if they take this image of the risk perceiver into account.

References

[1] Morrall, J.F. (1986), III, *A review of the record.* Regulation, (Nov/Dec): pp. 25-34.

[2] Tengs, O.T., *et al.* (1995), *Five-hundred life saving interventions and their cost effectiveness.* Risk Analysis. 15: pp. 369-390.

[3] Ramsberg, J. and L. Sjöberg (1997), *The cost-effectiveness of life saving interventions in Sweden.* Risk Analysis. 17: pp. 467-478.

[4] Sunstein, C.R. (2002), *Risk and reason. Safety, law, and the environment.* Cambridge University Press, Cambridge, United Kingdom.

[5] Ramsberg, J. and L. Sjöberg (1998), *The importance of cost and risk characteristics for attitudes towards lifesaving interventions.* Risk - Health, Safety & Environment. 9: pp. 271-290.

[6] Sjöberg, L. (1996), *Risk perceptions by politicians and the public*. Center for Risk Research, Stockholm.

[7] Sjöberg, L. (1999), *Risk perception in Western Europe.* Ambio. 28: pp. 543-549.

[8] Sjöberg, L., *Local acceptance of a high-level nuclear waste repository.* Risk Analysis, in press.

[9] Sjöberg, L. and B.-M. Drottz-Sjöberg (1993), *Attitudes to nuclear waste*. Center for Risk Research, Stockholm.

[10] Sjöberg, L. (1989), *Mood and expectation*, in *Cognition in individual and social contexts*, A.F. Bennett and K.M. McConkey, Editors. Elsevier, Amsterdam, pp. 337-348.

[11] Kahneman, D. and A. Tversky (1979), *Prospect theory: An analysis of decisions under risk.* Econometrica, 47: pp. 263-291.

[12] Sjöberg, L. and B.-M. Drottz-Sjöberg (1994), *Risk perception of nuclear waste: experts and the public*, Center for Risk Research, Stockholm School of Economics.

[13] Sjöberg, L. and B.-M. Drottz-Sjöberg (2001), *Fairness, risk and risk tolerance in the siting of a nuclear waste repository,* Journal of Risk Research, 4: pp. 75-102.

[14] Dunlap, R.E., M.E. Kraft, and E.A. Rosa (1993), eds. *Public reactions to nuclear waste*. Public reactions to nuclear waste, ed. R.E. Dunlap, M.E. Kraft, and E.A. Rosa., Duke University Press, Durham.

[15] Sjöberg, L., M. Viklund, and J. Truedsson (1999), *Attitudes and opposition in siting a high level nuclear waste repository*, in *Facility Siting: Issues and Perspectives*. Academia Sinica: Columbia Earthscape Research.

[16] Särskilde rådgivaren inom kärnavfallsområdet, *Plats för slutförvaring av kärnavfall? Förstudier i åtta kommuner. (A site for a final nuclear waste repository? Pilot studies in eight municipalities).* SOU. Vol. SOU 2002:46, 2002, Stockholm: Regeringskansliet.

[17] National Council for Nuclear Waste (KASAM) (2001), *Feasibility study municipalities in dialogue with the public: The examples of Nyköping, Oskarshamn and Tierp.* SOU 2001: 35, Stockholm: Government Printing Office.

[18] Sundqvist (2002), G., *The bedrock of opinion. Science, technology and society in the siting of high-level nuclear waste*. Dordrecht, the Netherlands: Kluwer.

[19] Sjöberg, L. and B.-M. Drottz (1987), "Psychological reactions to cancer risks after the Chernobyl accident". Medical Oncology and Tumor Pharmacotherapy, 4: pp. 259-271.

[20] Douglas, M. and A. Wildavsky (1982), *Risk and culture*. Berkeley, CA: University of California Press.

[21] Wildavsky, A. and K. Dake (1990), "Theories of risk perception: Who fears what and why?" in Daedalu*s*, pp. 41-60.

[22] Boholm (1996), Å. *The cultural theory of risk: an anthropological critique.* Ethnos, 61: pp. 64-84.

[23] Sjöberg (1997), L., *Explaining risk perception: An empirical and quantitative evaluation of cultural theory.* Risk Decision and Policy, 2: pp. 113-130.

[24.] Boholm (1998), Å. *Visual images and risk messages: commemorating Chernobyl.* Risk Decision and Policy, 3: pp. 125-143.

[25.] Boholm (2003), Å. *The cultural nature of risk: Can there be an anthropology of uncertainty?* Ethnos, 68(2): pp. 159-178.

[26.] Fischhoff (1978), B., et al., *How safe is safe enough? A psychometric study of attitudes towards technological risks and benefits.* Policy Sciences, 9: pp. 127-152.

[27.] Slovic (1987), P., *Perception of risk.* Science, 236: pp. 280-285.

[28.] Slovic (1991), P., J.H. Flynn, and M. Layman, *Perceived risk, trust, and the politics of nuclear waste.* Science, 254: pp. 1603-1607.

[29] Slovic, P. (2000), ed. *The perception of risk*, Earthscan, London.

[30] Flynn, J., *et al.* (1992), *Trust as a determinant of opposition to a high-level radioactive waste repository: Analysis of a structural model.* Risk Analysis, 12: pp. 417-429.

[31] Weinstein, N.D. (1989), *Optimistic biases about personal risks.* Science, 185: pp. 1232-1233.

[32] Weinstein, N.D. (1980), *Unrealistic optimism about future life events.* Journal of Personality and Social Psychology, 39: pp. 806-820.

[33] Sjöberg, L. (2000), *The different dynamics of personal and general risk*, in *Foresight and precaution. Volume 1*, M.P. Cottam, *et al*., Editors, A. A. Balkema: Rotterdam. pp. 1149-1155.

[34] Sjöberg, L. (2003), *The different dynamics of personal and general risk.* Risk Management: An International Journal, 5: pp. 19-34.

[35] Flynn, J., P. Slovic, and H. Kunreuther (2001), eds. *Risk, media, and stigma. Understanding public challenges to modern science and technology*, Earthscan: London.

[36] Loewenstein, G.F. (2001), *et al.*, *Risk as feelings.* Psychological Bulletin, 127: pp. 267-286.

[37] Finucane, M.L., *et al.* (2000), *The affect heuristic in judgments of risks and benefits.* Journal of Behavioral Decision Making, 13: pp. 1-17.

[38] Slovic, P., B. Fischhoff, and S. Lichtenstein (1979), *Rating the risks.* Environment, 21(3): pp. 14-20, 36-39.

[39] Fischhoff, B., P. Slovic, and S. Lichtenstein (1982), *Lay foibles and expert fables in judgments about risk.* American Statistician, 36: pp. 240-255.

[40] Rowe, G. and G. Wright (2001), *Differences in expert and lay judgments of risk: myth or reality?* Risk Analysis, 21: pp. 341-356.

[41] Sjöberg, L. (2002), *The allegedly simple structure of experts' risk perception: An urban legend in risk research.* Science, Technology and Human Values, 27: pp. 443-459.

[42] Sjöberg, L. (2002), *Are received risk perception models alive and well?* Risk Analysis, 22: pp. 665-670.

[43] Gardner, G.T. and L.C. Gould (1989), *Public perceptions of the risk and benefits of technology.* Risk Analysis, 9: pp. 225-242.

[44] Sjöberg, L. (2000), *Perceived risk and tampering with nature.* Journal of Risk Research, 3: pp. 353-367.

[45] Sjöberg, L. and E. Winroth (1986), *Risk, moral value of actions, and mood.* Scandinavian Journal of Psychology, 27: pp. 191-208.

[46] Sjöberg, L. (2003), *Risk perception, emotion, and policy: The case of nuclear technology.* European Review, 11: pp. 109-128.

[47] Lerner, J.S., *et al.* (2003), *Effects of fear and anger on perceived risks of terrorism: A national field experiment.* Psychological Science, 14: pp. 144-150.

[48] Sjöberg, L., *Explaining individual risk perception: the case of nuclear waste.* Risk Management: An International Journal, in press.

[49] Sjöberg, L., *The perceived risk of terrorism.* Risk Analysis, in press.

[50] Bassett, J., G. W. and R.C. Hemphill (1991), *Comments on "Perceived risk, stigma, and potential economic impact of a high-level nuclear waste repository in Nevada"*. Risk Analysis,. 11: pp. 697-700.

[51] Broström, L., et al. (2002), *Psykosociala effekter av ett djupförvar för använt kärnbränsle. Litterturöversikt och intervjuer med Uppsalabor. (Psychosocial effects of a depth repository for spent nuclear fuel. Literature review and interviews with residents of Uppsala)*, SKB: Stockholm.

[52] Sjöberg, L. (2000), *Factors in risk perception.* Risk Analysis, 20: pp. 1-11.

[53] Sjöberg, L. (2000), *Specifying factors in radiation risk perception.* Scandinavian Journal of Psychology, 41: pp. 169-174.

[54] Sjöberg, L., *Will the real meaning of affect please stand up?* Journal of Risk Research, in press.

[55] Sjöberg, L. (1999), *Consequences of perceived risk: Demand for mitigation.* Journal of Risk Research, 2: pp. 129-149.

[56] Sjöberg, L. (2000), *Consequences matter, "risk" is marginal.* Journal of Risk Research, 3: pp. 287-295.

[57] Sunstein, C.R. (2003), *Terrorism and probability neglect.* Journal of Risk and Uncertainty, 26: pp. 121-136.

[58] Sjöberg, L. (2002), *Attitudes to technology and risk: Going beyond what is immediately given.* Policy Sciences, 35: pp. 379-400.

[59] Sjöberg, L. (1999), *Perceived competence and motivation in industry and government as factors in risk perception*, in *Social trust and the management of risk*, G. Cvetkovich and R.E. Löfstedt, Editors, Earthscan: London. pp. 89-99.

[60] Viklund, M. (2003), *Trust and risk perception: a West European cross-national study.* Risk Analysis, 23: pp. 727-738.

[61] Drottz-Sjöberg, B.-M. (1996), *Stämningar i Storuman efter folkomröstningen om ett djupförvar. (Moods in Storuman after the repository referendum)*, SKB: Stockholm.

[62] Drottz-Sjöberg, B.-M. (1998), *Stämningar i Malå efter folkomröstningen 1997. (Moods in Malå after the 1997 referendum)*. SKB: Stockholm.

[63] Sjöberg, L. and A. af Wåhlberg (2002), *New Age and risk perception.* Risk Analysis, 22: pp. 751-764.

[64] Sjöberg, L. (2003), *Distal factors in risk perception.* Journal of Risk Research, 6: pp. 187-212.

[65] Peters, E. and P. Slovic (1996), *The role of affect and worldviews as orienting dispositions in the perception and acceptance of nuclear power.* Journal of Applied Social Psychology, 26: pp. 1427-1453.

[66] Jasanoff, S. (1998), *The political science of risk perception.* Reliability Engineering and System Safety, 59: pp. 91-99.

[67] Sjöberg, L. (2001), *Political decisions and public risk perception.* Reliability Engineering and Systems Safety, 72: pp. 115-124.

[68] Sjöberg, L. (2001), *Whose risk perception should influence decisions?* Reliability Engineering and Systems Safety, 72: pp. 149-152.

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THE COLLECTION OF EXPERT JUDGEMENTS FOR ENVIRONMENTAL RISK STUDIES

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Analyses of the environment are inherently complex and require the specification of many parameters and relationships. Often these analyses are implemented as computer simulation models which allow for various scenarios to develop and facilitate expressing uncertainty about the models predictions. This uncertainty is driven by the uncertainty in the models, the relationships, and the parameters employed in the analysis. The focus of this presentation is on capturing the uncertainty in parameters so that it may be realistically propagated through the analysis.

When available, data from experiments or the field can be used in this quantification. But often, these sources of data are not fully adequate because the situation under which the data are gathered and the situation represented by the model differ. For example, it may be necessary to scale up from a lab experiment to a field setting or a safe analog may have been substituted for a dangerous material. Moreover, there may be conflicting pieces of evidence that require interpretation and reconciliation. It is also common for risk models to produce estimates of uncertainty in risk and well as point estimates of risk. For all these reasons, expert human judgements have played a role in quantification of risk models.

Human judgements can enter a risk study in various ways. An analyst may need to provide a value for a parameter and therefore searches for information to support the quantification. Suppose that the analyst encounters several, perhaps disparate, sources of information. The analyst might choose to select one source of information as being primary and use a value suggested by that study. Conversely, the analyst may decide that all sources of information are relevant and decide to take an average or integrate the results by some other means. But what about the uncertainty that is present in the original studies and the uncertainty that is introduced by the analyst's choice? How is this uncertainty to be expressed? It may be that the uncertainty is just ignored or a rule of thumb such as using an error factor is used. What has become a poor representation of uncertainty may become worse because the methodology and rationales for decisions may not be documented. Traceability is lost and the meaning of the risk estimates obtained become cloudy.

Alternatively, the inclusion of human judgements, judgements based on evidence, can be based on a more structured and more scrutable set of procedures. Over the last thirty years, a knowledge base for the collection and processing of such judgements has emerged from the fields of psychology, statistics, and decision and risk analysis. From this data base an approach has evolved has been termed Formal Elicitation [Bonano *et al.* 1989, Cooke 1991]. It entails a structured approach to obtaining the judgements from one more experts and processing those judgements to produce probability distributions for uncertain parameters. The formal structure treats:

- Selection and specification of quantities to be assessed.
- Qualification and selection of experts.

- Organisation of the experts.
- Elicitation of individual judgements.
- Reconciling and combining judgements.
- Documentation of the process and expert rationales.

Formal Elicitation has been used for a number of risk studies [USNRC 1990, Kotra *et al.* 1996, HARPER *et al.* 1994, Trauth, Hora and Guzowski 1994. Rechard *et al.* 1993, Trauth, Hora, and Rechard, 1993, Wheeler, Hora, Unwin, and Cramond. 1988]. It provides a reasoned approach to incorporating judgements into studies and is particularly valuable where a process is needed that will stand up to public scrutiny and legal challenges.

Ever since the landmark WASH-1400 Reactor Safety Study [USNRC 1975], there has been an awareness in the risk analysis community that the quantification of uncertainty distributions cannot always be made directly from the data at hand. In such instances, experts have been employed to interpret the available data and express their interpretations in the form of probabilities of events and probability distributions for quantities.

Some situations that favour the use of experts include:

- Conflicting data sources.
- Data collected using laboratory scale experiments where the uncertainty is on a field scale.
- Unverified models or measuring procedures.
- Analog chemicals and tracer elements.
- Limited evidence.
- Data insufficient to internally estimate uncertainty.

Formal elicitation programmes are not without their drawbacks, however. The formal structure means that more time and resources must be applied. Often multiple external experts are employed and these experts must be compensated. Using formal methods to treat every uncertain value in an analysis is therefore unwarranted. These resource intensive methods should be used for those key parameters and uncertainties that are seen to be most important in shaping the estimates of risk and uncertainty.

Next, we describe the essential elements of a formal elicitation process. There are options with each of these elements, but each element needs to be considered in building a process.

Selecting issues and specifying questions

As mentioned earlier, not all uncertainties should be treated using a formal process. The parameters should be, first, important contributors to risk and uncertainty. This is normally determined through preliminary sensitivity studies. Second, the task of quantification should not be trivial. If there is strong evidence that all would agree upon and that evidence leads to a relatively unambiguous distribution, why bother to bring in experts? Third, there must be an available pool of expertise. If you can not find experts to address the issue or if there is not evidential basis for making the judgements, the product of the effort will not stand up to scrutiny.

Perhaps the most unacknowledged difficulty in obtaining expert judgements is the specification of the explicit issues to be addressed. It seems as this would be a simple a matter, but often the interpretations of issues differ among the experts and between the study staff and the external experts. Questions should not be asked about parameters and values that are specific to a model. The questions should be about quantities whose values can be, at least theoretically, be ascertained in the environment.

Another difficulty that sometimes presents itself is sorting out the sources of uncertainty that should be included in the experts' assessments. For example, if the experts were provide uncertainty distributions for the amount of radioactivity left in the surface soil in grassland, should the length of grass, the precipitation, etc. be included as factors causing uncertainty or should these values be specified as conditions for the assessment?

Selecting the experts

There are several issues here:

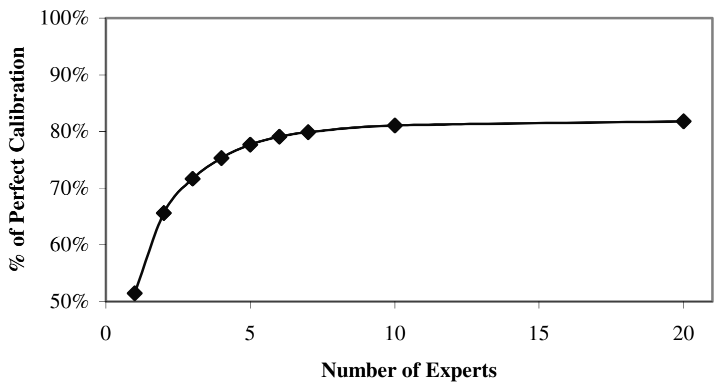
- How does one qualify experts?
- How should the expert be selected?
- How many experts should be selected?

The qualification of experts should be based on some documented criteria. These criteria can include measures of expertise such as degrees, publications, positions, etc. Additionally, the experts should be free from "motivational biases". A motivational bias is a real or perceived circumstance that could lead an expert to provide answer that are not neutral from a scientific basis. A person with strong political view either for or against a project may intentionally or unintentionally provide a biased opinion. Similarly, a person with an economic stake in the outcome of a study (such as the employee of an operating company) may be swayed. The perception, as well as the reality, of a motivational bias should be guarded against.

The selection of the experts may be done by the study staff or it can be "out-sourced" to an advisory group. This may be a good tactic in circumstances where the subject is under intense public debate.

The question of how many experts should be selected depends in part upon the breadth of the issues and the method of organising the experts. When experts are organised as teams, each team normally provides a single assessment. When experts work individually, each expert provides an assessment. What ever the form of organisation, there appears to be growing evidence that the number of assessments should be between three and six. Figure 1 shows a graph of the calibration of varying size groups of experts participating in training exercises for the NUREG-1150 study [Hora 2003]. The vertical axis is scaled from 0% to 100% and reflects how faithful the assessments are in the following sense: 100X% of the actual values on training questions should be found in the lower X-probability tails of the respective distributions. The graph shows that the calibration improves rapidly from one to five or six experts but only a little after six.

Figure 1. **Average calibration score of expert groups**



Organising the experts

We have already mentioned that experts can be organised in teams or they can work individually. Teams are useful when the issues addressed span several different disciplines. Each team member takes the lead in their own area of expertise. In designing markers for nuclear waste disposal, a team might be composed of a linguist, a materials scientist, an architect or mechanical engineer, and an archaeologist [Trauth, Hora and Guzowski, 1992].

More often, the experts work individually but with the possibility of interaction. In some studies the experts have worked in total isolation, in others they are required to meet and exchange views. Isolated experts are more independent (good) but perhaps less knowledgeable (bad). It is our opinion that the experts should interact but be required to make their assessments independently. The appears to be real advantage in having some redundancy otherwise the expressed uncertainty is likely to be less that the uncertainty that is really there.

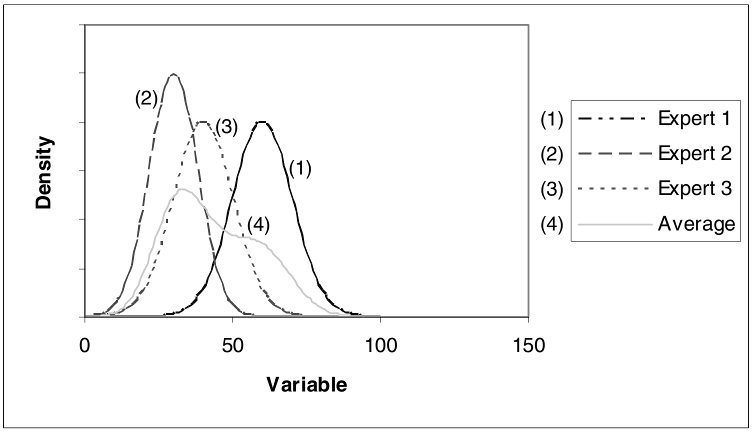
Several studies in the United States have used a multiple meeting format [see USNRC 1990, Bonano *et al.* 1989, Kotra *et al.* 1996 for references]. The experts have an initial meeting, participate in probability training and exercises, and openly discuss the issues, the methods, and the data relevant to the problem. The experts then disperse and study the problem by examining data sources, running analyses, etc. They return after, perhaps, one month and again exchange views. This exchange is followed by formal probability elicitation conducted by a team of specialists individually with each expert.

Reconciling and combining judgements

The expression of uncertainty about a quantity is usually accomplished by asking the expert to given certain cumulative probabilities – for example the 0%, 5%, 25%, 50%, 75%, 95%, and 100% points on a distribution function [Hora, Hora, and Dodd 1992]. These values give a good indication of the location and shape of the uncertainty distribution but they do not completely specify the distribution. This is usually accomplished by interpolating between the points. In those instances where the 0% and/or 100% points have not been obtained it may be necessary to extrapolate to obtain the tails of the distribution. Extrapolation is much more difficult than interpolation and it is better not to get into this situation.

We have earlier made the case for redundancy among the experts. Redundancy is important in that it allows us to capture the differences among the experts' judgements as well as the internal uncertainty expressed in each individual judgement. Figure 2 shows the hypothetical distributions provided by each of three experts and then an aggregated distribution that is simple the average of the three component distributions. The spread of the aggregated distribution is clearly greater because it incorporates both sources of uncertainty – intra- and inter-expert.

Figure 2. **Averaging three densities**



The simple averaging aggregation rule employed in Figure 2 is perhaps the most widely used aggregation rule for multiple experts. This method is well received for several practical reasons:

- It is robust.
- It is transparent and easily comprehended.
- It preserves the total uncertainty expressed by multiple judges.
- It avoids differentially weighting experts.

Genest and Zidek (1992), and Clemen and Winkler (1997) provide extensive discussions of combining experts. Also see Cooke (1990).

Documentation of the process and expert rationales

While the numerical results of a probability elicitation exercise provide the data to be input in computer codes for the evaluation of risks, the numbers by themselves are not sufficient to make a case. The rationales the experts used to reach their judgements, the models and data sources, the places where they agree and disagree must be documented in order to provide a base of support for the values. This is an important step in concluding the process and should not be ignored.

It is also important to document the process and procedures used in the exercise. For example, sometimes more attention is paid to how the experts were selected than to the judgements the experts have provided.

References

Bonano, E.J., S.C. Hora, R.L. Keeney, and D. von Winterfeldt (1989), *Elicitation and Use of Expert Judgement in Performance Assessment for High-level Radioactive Waste Repositories,* U.S. Nuclear Regulatory Commission, NUREG/CR-5411.

Clemen, R.T. and R.L. Winkler (1997), “Combining Probability Distributions from Experts in Risk Analysis” *Risk Analysis,* 19, pp. 187-203.

Cooke, R.M (1991), *Experts in Uncertainty,* Oxford University Press, Oxford.

Genest, C. and J.V. Zidek (1986), “Combining Probability Distributions: A Critique and Annotated Bibliography”. *Statistical Science,* 1, 114-48.

Harper, F.T., S.C. Hora, M.L. Young, L.A. Miller, C.H. Lui, M.D. Mckay, J.C. Helton., L.H.J. Goossens, R.M. Cooke, J.P¨Asler-Sauer, B. Kraan, J.A. Jones (1994), *Probability Accident Consequence Uncertainty Analysis*, Nureg/Cr-6244 Eur 15855en Sand94-1453.

Hora, S.C (2003), Probability Judgements for Continuous Quantities: Linear Combinations and Calibration, in review.

Hora, S.C., Hora, J.A., Dodd, N.G. (1992), “Assessment of Probability Distributions for Continuous Random Variables: A Comparison of the Bisection and Fixed Value Methods”, *Organizational Behavior and Human Decision Processes,* 51, 133-155.

Juslin, P. (1994), “The overconfidence phenomenon as a consequence of informal experimenter-guided selection of almanac items”. *Organizational Behavior & Human Decision Processes,* 57(2), Feb 1994, 226-246.

Kotra, J.P., M.P. Lee, N.A. Eisenberg, and A.R. DeWispelare (1996), *Branch Technical Position on the Use of Expert Elicitation in the High-level Radioactive Waste Program,* U.S. Nuclear Regulatory Commission, NUREG-1563.

Rechard, R.P., K, Trauth, J.S. Rath, R.V. Guzowski, S.C. Hora and M.S. Tierny (1993), *The Use of Formal and Informal Expert Judgements when Interpreting Data for Performance Assessments* SAND92-1148, Sandia National Laboratories.

Trauth, K. S.C. Hora, and R.P. Rechard (1993), *Expert Judgement as Input to Waste Isolation Pilot Plant Performance-Assessment Calculations*, SAND91-0625, Sandia National Laboratories.

Trauth, K., S.C. Hora and R.V. Guzowski (1992), *Expert Judgement on Markers to Deter Inadvertent Human Intrusion into the Waste Isolation Pilot Plant*, SAND92-1382, Sandia National Laboratories.

Trauth, K., S.C. Hora and R.V. Guzowski. (1994), *A Formal Expert Judgement Procedure for Performance Assessments of the Waste Isolation Pilot Plant,* SAND93-2450, Sandia National Laboratories.

Trauth, K., S.C. Hora and R.V. Guzowski (1994), *A Formal Expert Judgement Procedure for Performance Assessments of the Waste Isolation Pilot Plant*, SAND93-2450, Sandia National Laboratories.

U. S. Nuclear Regulatory Commission (1990), *NUREG-1150: Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants, Vols. 1-3, Final Report.*

U.S. Nuclear Regulatory Commission (1975), *Reactor Safety Study: WASH-1400,* NUREG-751014.

Wheeler, T., S.C. Hora, S. Unwin, and W. Cramond (1998), *Results of the Expert Opinion Elicitation of Internal Event Front-End Issues for NUREG 1150: Expert Panels* NUREG/CR-5116 Vol 1 and Sand 88-0642, Sandia National Laboratories.

SURVEY OF THE ROLE OF UNCERTAINTY AND RISK IN CURRENT REGULATIONS[1]

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Introduction

This paper provides an overview of the different standards adopted by regulators in different countries for determining the safety of radioactive waste facilities, and of the different approaches adopted by regulators for determining how uncertainties are treated in safety cases for such facilities.

The aim of the paper is to identify both common approaches and differences between regulations and guidance in different countries. It is also intended that the paper should act as an introduction to the issues to be discussed at the Workshop.

Regulations and guidance include two broad categories of criteria: numerical and qualitative. Numerical criteria are both relatively easy to compare between different regulations and also to use simplistically in assessing a safety case. In the same way that numerical criteria should not provide the sole basis for determining safety, they are not the only type of standard for which a comparison is useful. There are many qualitative requirements in regulations and guidance, including transparency and traceability, quality assurance, sound science and engineering, and optimisation. However, this paper is limited to a comparison of the ways in which different regulations address the issue of uncertainty.

Regulatory standards

In a discussion of regulatory standards for determining the safety of radioactive waste facilities, it is useful to distinguish between three levels of standards:

- Limits. A limit provides a value (e.g., for effective dose) that must not be exceeded.
- Constraints. A constraint provides a value (e.g., for site-related or source-related dose) that should not be exceeded.
- Targets. A target provides a numerical criterion against which information can be assessed. A target is sometimes termed an optimisation level.

1. The work reported in this paper has been funded by SKI, and the support of Eva Simic (SKI) is acknowledged.

Different levels may be specified within the same regulations. Within Europe for example, the Basic Safety Standards specify a dose limit to the public of 1 mSv/year for all man-made sources of radiation (excluding medical sources). Because individuals may be exposed to more than one exposure source but must remain within this overall limit, different countries then apply constraints and/or targets for site- or source-related exposure.

For example:

- in the Netherlands a dose constraint of 0.1 mSv/yr applies to waste management facilities and there is also a target or first optimisation goal of 0.04 mSv/yr;
- in the UK, there is a change from a dose constraint of 0.3 mSv/yr for a single new source to a risk target of 10^{-6}/yr at the time when control is withdrawn from the site;
- in Switzerland, a dose constraint of 0.1 mSv/yr applies to an average member of the population group most at risk for scenarios representative of the more likely future evolution scenarios. There is also a risk constraint of 10^{-6}/yr applicable to the sum of scenarios not considered in the comparison with the dose constraint.

In almost all cases, regulatory standards take the form of numerical criteria. Exceptionally a qualitative standard may be set. For example, in France a criteria based on the ALARA[2] principle has been established for the disposal of low-level radioactive waste. In this case, the proponent has proposed a dose constraint of 0.25 mSv/yr for the normal evolution scenario or any abnormal situation with a high probability of occurrence.

The numerical criteria in general use in regulations and guidance applicable to radioactive waste management are dose and risk. Within those regulations specifying a risk criterion, there is general agreement that a risk of 10^{-6} per year of suffering a serious health effect is an appropriate level as a regulatory constraint or target. There are differences relating to who is protected at this level, and also as to what constitutes a serious health effect. These differences are discussed in the following sections.

Within those regulations specifying a dose criterion, there is slightly less consistency concerning an appropriate value. Dose constraints typically range between 0.1 and 0.5 mSv/yr. As with risk criteria, there are also differences as to who is protected, but all the dose criteria are based on an annual individual dose.[3]

Serious health effects

A key element of any quantitative assessment of risk, be it probabilistic or deterministic, is accounting for the stochastic element of the response to any given dose. At dose rates below about 0.5 Sv/yr, not everyone exposed to a given dose will suffer a detectable health effect, and a dose to risk conversion factor is used to take account of this uncertainty. Some regulations state the factor to be used or require use of an appropriate ICRP value. Different values apply depending on the consequence considered. In the UK, for example, the guidance includes reference to a value of 0.06 per Sv, established by ICRP for the:

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2. ALARA – As Low As Reasonably Achievable.
3. Where regulations are more specific in terms of the dose to be calculated, they generally refer to an annual individual effective dose (i.e., the summation of the equivalent doses to the individual tissues of the body, weighted by the appropriate tissue weighting factor).

"… purpose of assessing the frequency of induction of fatal cancer and serious hereditary effects in a general population of all ages."

In Sweden, however, the recommended factor is 0.073 per Sv, which is the value established by ICRP to take account of cancer (fatal and non-fatal) as well as hereditary effects.

The corollary of this difference in factors is that a risk of 10^{-6} per year corresponds to a dose of 13.7 μSv/yr or 16.7 μSv/yr depending on whether non-fatal cancers are included in the definition of health effects. A 20% difference is small in comparison with some of the other uncertainties inherent in assessments, but it highlights the importance of clarity when making and documenting all the assumptions in a safety case.

Values for the dose to risk factor are based on epidemiological information, which is periodically re-assessed, particularly as estimates of exposure to past sources of radiation are revised. Over time, therefore, the same level of exposure may be assessed as giving rise to a different level of risk. Conversely, dose criteria may need to be changed periodically to ensure a consistent level of protection in terms of actual consequences (e.g. numbers of people suffering a serious health effect).

For most stakeholders, a value of dose has no implicit meaning and must be compared to some other dose (e.g., from background radiation) or otherwise converted to a consequence that can be interpreted from experience. The dose to risk factor or a similar conversion may therefore also be relevant if the regulatory end-point is dose.

Protected individuals

Regulations need to specify to whom the dose or risk criteria apply. There are two principal approaches; a representative member of an exposed group, or a reasonably maximally exposed individual (RMEI). The approach based on a representative member of a group is an extension of the critical group concept used in regulating routine releases from operating plants. In the UK, the guidance adopts the term potentially exposed group (PEG) to clarify that there is uncertainty regarding the location of any release. Other regulations and guidance based on the same concept do not apply the same terminology, but there is generally a requirement to consider a number of groups so as to identify the most significant in terms of dose or risk.

The extent to which regulations specify the groups or activities to be considered varies. Some guidance is generally provided on the extent to which human intrusion should be considered. Typical activities that may be prescribed include subsistence farming, and groundwater abstraction for drinking and irrigation. Regulations and guidance may also specifically exclude activities from regulatory concern. No regulations currently require consideration of deliberate intrusion and certain other types of human activity may also be excluded.

ICRP provides guidance on the identification of the critical group that can, by extension, be applied to the definition of exposed groups. However, since the exposed group does not comprise specific individuals with particular characteristics and patterns of behaviour, the range of characteristics from which a representative member is identified is a modelling assumption, rather than an observation. In fact, for most assessment approaches, the range is unimportant and the only purpose of applying protection standards to a group is to ensure that extreme individual behaviour does not drive decision making. This leads to the alternative approach of protecting the RMEI as required, for example, by the regulations promulgated for Yucca Mountain. Again, extreme individual behaviour is avoided by requiring that the protected individual's behaviour and characteristics are "reasonable".

In the case of deterministic calculations, there may be little difference between results for an exposed group or the RMEI. Probabilistic evaluations may result in some calculated differences depending on the extent to which the location and characteristics of the exposed group are treated probabilistically.

Other numerical criteria

As an alternative to dose or risk, some regulations specify fluxes or release rates at particular points or boundaries, either as supplementary criteria to dose or risk or as a "surrogate" for such measures. In the USA, for example, cumulative releases over a period of 10 000 years is used as a regulatory standard for the WIPP site. In Finland, STUK has established a set of nuclide-specific activity release constraints for fluxes at the geosphere-biosphere boundary.

A further example of supplementary criteria is radionuclide concentration: maximum radionuclide concentrations are specified in the groundwater protection standards for both the WIPP and Yucca Mountain. A recent IAEA report[4] discusses other measures that could be developed into supplementary numerical criteria.

A perceived benefit of these supplementary criteria is that they avoid the need to make assumptions concerning the biosphere and protected individuals. However, in order to set numerical values for this type of criteria, the significance of fluxes, release rates or concentrations must be assessed and this can only be done by making assumptions about receptors. The key difference, therefore, is that it is the regulator who is required to make assumptions about the biosphere and protected individuals rather than the developer. Since regulations are normally established in advance of site selection, this approach also means that these assumptions are likely to be generic rather than site-specific.

Some regulations and guidance include limits on the timescales to be considered in assessments. These could be regarded as numerical criteria, but such limits are generally set so as to take account of varying levels of uncertainty so they are discussed in the following section.

Treatment of uncertainty

In general terms, regulators can adopt three different approaches to determining how uncertainties are treated in safety case for radioactive waste facilities:

- Prescriptive regulations could be promulgated to require the developer to consider particular types of uncertainty in a particular manner.
- Regulatory guidance could be issued to ensure that the developer is aware of the issues of concern to the regulator and, in appropriate circumstances, indicate specific approaches or methods that the regulator would like to be used or followed.
- Regulatory review of methodologies and approaches developed by the proponent. This review may be supported by independent calculations, but these do not constrain the approach used by the proponent.

4. IAEA, 2003. Safety indicators for the safety assessment of radioactive waste disposal. IAEA-TECDOC-1372. Vienna, IAEA.

The choice between these various regulatory responses is related as much to the established style of regulation in a particular country as it is to the different types of uncertainties to be considered. There are overlaps between these approaches, and the majority of regulations and guidance are based on a combination of the last two approaches. The USA provides the key examples of the first approach, with the regulations applicable to the WIPP and Yucca Mountain both including prescriptive elements that require the developer to consider particular scenarios and human intrusion activities and to adopt a particular assessment approach. The regulatory end-point for the WIPP, for example, requires the use of probabilistic calculations. The regulations for Yucca Mountain expect the use of probabilistic methods for calculating dose.

Two key areas of uncertainty that are addressed in the majority of regulations and guidance are timescales and scenarios. The various approaches adopted for these topics are outlined below.

Timescales

A key source of uncertainty in assessments of long-term performance is time-dependent changes in the natural environment and in the properties of barrier systems. These uncertainties increase with time and there is a general acknowledgement that different levels of detail are appropriate for different assessments over different timescales.

Irreducible uncertainties about the natural environment limit the timescales over which quantitative assessments can be applied. Over longer timescales, many regulations expect alternative approaches to assuring safety, generally based on qualitative arguments. Conversely, some regulations expect more detailed assessments for the relative short-term after closure. Whatever the regulatory requirements and expectations concerning the level of detail in assessments, no examples were found in which the regulatory criteria change with the timescale considered.

The following specific examples illustrate the differences in the extent to which regulations prescribe the timescales to be considered:

- WIPP – the principal regulatory criterion is based on cumulative releases over 10 000 years.
- Yucca Mt – the individual and groundwater protection criteria apply for 10 000 years. The safety case must consider human intrusion for the same period or until the time that degraded waste packages would no longer be recognised during drilling.
- Sweden – The regulations consider it feasible to model system evolution for the first 1 000 years after closure. Beyond this time, assessments of system evolution are expected to be based on a series of different scenarios.
- Finland – The importance of scenarios that cannot be assessed through quantitative analyses should be examined through complementary considerations such as bounding analyses and comparison with natural analogues. The importance of such considerations increases as the assessment period increases. Judgements of safety beyond 1 million years can be based mainly on complementary considerations.
- UK – The regulatory guidance does not prescribe an overall timescale for assessments. Assessments are expected to cover the period over which models and data can be demonstrated to have validity. Performance over longer timescales may be based on scoping calculations and qualitative information.

Scenarios

The evolution of a radioactive waste disposal system, including both constructed barriers and the natural environment, is dependent on a wide variety of features, events and processes (FEPs). Groups of such FEPs, taken together, form scenarios that describe in broad terms the patterns of influence to be considered in assessments. Regulations and guidance are variable in the extent to which they specify the scenarios to be considered in a safety case.

A normal evolution scenario, including the events and processes expected to occur, is implicitly or explicitly required in all regulations. An assessment of human intrusion is also required in all cases, although the results of this assessment are not necessarily required to be integrated with other scenarios or compared against the same criteria as the normal evolution scenario.

Most regulations require the consideration of variant scenarios, although generally only broad descriptions of the events and processes to be considered are provided. For example, Finnish guidance requires consideration of variant scenarios based on declined performance of single barriers or, where the behaviour of barriers is coupled, multiple barriers. The French safety rules require consideration of a reference scenario that includes gradual degradation of the barriers and highly probable natural events. Variant scenarios must be considered for highly uncertain events or likely events of exceptional magnitude.

Regulations may also exclude specific events or processes from assessment calculations. For example, Swiss Protection Objectives exclude scenarios with more serious non-radiological consequences or with extremely low probability. In France, an Appendix to the safety rule describes various mining and similar activities applicable to different rock types and notes those that can be excluded from assessment calculations. In the USA, the regulations for the WIPP site describe the scope and extent of mining operations to be considered in the assessment and specifically exclude other mining operations and similar activities.

Conclusions

This paper has examined a range of regulations and guidance relevant to the authorisation of facilities for the disposal of radioactive waste. There are broad similarities between the requirements included in regulations that have a risk criterion. Regulations with dose criteria show a wider range, particularly in the value of the numerical criteria, but also in other aspects of the treatment of uncertainty such as the extent of variant scenarios to be considered.

Key issues include the practical significance of constraints and targets for dose and risk rather than site- or source-related limits. A related issue is the importance of numerical compliance versus the fulfilling of qualitative criteria. Differences between the dose constraints may give rise to questions from stakeholders in particular countries. Questions may also be raised by some stakeholders about the basis and justification for the apparent addition of an extra level of protection when a risk criterion is adopted.

MANAGEMENT OF UNCERTAINTIES AND THE ROLE OF RISK IN ANDRA'S PROGRAMME

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This paper aims at presenting some aspects of the management of uncertainties in the programmes of Andra for the study of a deep geological repository for high level, long-lived wastes. After presenting very briefly the context of risk-management in the French safety rules, it will discuss how Andra has attempted to link the notions of uncertainties and risk in its "Dossier 2001" for the clay medium, how this could be made compatible with a deterministic safety approach, what feedback it got from this first exercise, and what are the perspectives for future work.

The French regulation and standards require safety analysis for repositories to be performed in a deterministic manner. In terms of design, it relies on the concept of "defense-in-depth", that requires to define multiple lines of defense, or multiple safety functions, so as to reduce risk as reasonably as possible, regardless of the probability of each identified risk. In terms of quantitative evaluations for the long term, the Basic Safety Rule III.2.f. recommends the use of a limited number of scenarios (both "normal evolution" and "altered evolutions") to represent the various situations that can occur in the repository, and to evaluate them in terms of effective dose. The normal evolution is characterised by an (implicit) reference to probability, as the Basic Rule states that is should correspond to *"the foreseeable evolution of the repository as regards certain or very probable events*". As regards altered evolutions, the acceptability of their impacts should be assessed "*with allowance made for the nature of the situations taken into consideration, the duration and the nature of the transfers of radioactive substances to the biosphere, the properties of the pathways by which man can be affected and the sizes of the groups exposed*". The use of risk, meaning the product of a probability by an exposure, is envisioned as a possible complementary indicator. However, the RFS expresses doubts about the use of such an indicator, since it "*may imply a debatable equivalence between reducing the probability and reducing the exposure*". Such a notion is, in practice, rarely used in an explicit manner in safety assessments performed on French repositories.

Andra has tried to implement methods for the management of uncertainties in all steps of its research programme for the study of a repository in clay. Risk was used as a tool in the context of the dossier 2001. First of all, it is important to give an overview of the various meanings of "risk" as used in the Andra's practice:

- "risk" is defined, inside Andra, as the characterisation of a potential danger in terms of probability and gravity. The product of both is rarely considered. Therefore, such expressions as "the probability of a risk" or "the gravity of a risk" refer to two independent variables.
- "risk", in such expressions as "risk analysis", refer to the methods used in the field of both nuclear and non-nuclear industry, to identify potential sources of danger and hierarchise them. A "risk" analysis does not always imply the characterisation of the various sources of

danger by a risk indicator, though their classification always imply some notion, even qualitative, of the relative likelihood and gravity of each individual source.

At the stage of the dossier 2001, the aim was to address uncertainties throughout the safety evaluation, by referring to notions of risk analysis. Various types of uncertainties were addressed, that could roughly be categorised into three different types. Those were uncertainties in the understanding of the phenomenology of the repository, uncertainties in the way its evolution is modelled and predicted, uncertainties in the occurrence of future events (such as boreholes, earthquakes, climate changes, etc.). This simple categorisation did not intend to cover exhaustively all types of potential uncertainties. It could be refined if needed; for example, uncertainties on the understanding of the phenomenology might be due to the lack of data, to the variability through time and space of the data, to the limited understanding of a phenomenon that can be accessible at a given time, to the long timescales involved.

The idea behind the analysis of uncertainties in the "dossier 2001" was to treat them, especially phenomenological uncertainties and uncertainties on future events, as "risks" for the repository not to behave as expected. This analogy between uncertainty and risk allowed the use of methods of risk management commonly employed in other fields of industry to perform the management of uncertainties. These methods use the concept of gravity and probability to rank the various sources of danger; such an approach had to be adapted in the context of long term safety. This process was called "qualitative safety analysis" (AQS).

The principle of the AQS was to identify the events, features and processes, both internal and external to the repository system, that could result in a malfunction of the repository. A malfunction was defined by reference to the functional analysis of the repository, that displayed a list of all the safety functions to be performed within the repository system. External events were identified by reference to national regulation or international FEP's databases (earthquake, glaciation, etc.). Relevant internal events and processes were derived from the uncertainties on the phenomenology identified in the scientific reports. Each uncertainty was converted into a possible malfunction of the repository system, and the relative ranking (equivalent, in terms of method, to a relative "probability" or "likelihood", but not used as such) of the corresponding event was derived from the level of uncertainty. This means that a possible malfunction was ranked higher (compared to others) if the underlying phenomenology was judged to be more uncertain. For example, at the stage of dossier 2001, the uncertainties on the geomechanical behaviour of the host rock lead to regard the development of an EDZ, potentially able to short-circuit the sealings, as "of a higher rank" than other types of dysfunctional processes.

The idea of the "ranking by expert judgement" was not to assess a "probability" of each event or process, but to give a sense of the relative importance of events, features, and processes, by laying more emphasis on those that were judged the more likely *or* the least characterised.

This process allowed to select sequences of events or processes that could be detrimental to the repository, in terms of effect on the various safety functions. Those that were equally detrimental, as regards safety functions, could be ranked if needed thanks to the ranking of individual uncertainties. These results were used both to hierarchise the situations, and to inform priorities for the future research programme (the higher the ranking of a particular sequence of events or processes, the more critical the underlying uncertainties). It was considered that the hierarchy of detrimental events could be related to the definition of scenarios, though this was not performed thoroughly at the stage of the dossier 2001.

Other uncertainties, essentially the uncertainties on models and parameters, were treated directly by the use of a quality assurance procedure. This required the choices of parameters to be presented in a pre-designed format, that displayed the various possible choices ("best estimate, conservative, maximum physically possible…"). Uncertainties were then treated by the choice of a "cautious but reasonable" value for each parameter. A later comparison with a probabilistic calculation showed the coherence between a deterministic and a probabilistic approach as long as they rely on the same underlying assumptions. However, the results of a probabilistic calculation, such as a distribution of expected dose, is difficult to use in a context where it is expected that the results of the calculation should be compared to a pre-defined threshold.

Feedback from this methodology was positive in the sense that it proved important to have a pre-defined strategy for the management of uncertainties. The exercise was also instrumental in underlying some difficulties in the application of procedures, or when explaining the methodologies to various evaluators. In particular, methods of risk management appeared to be complex as communication tools. Their adaptation to the context of management of uncertainties over long time-scales and progressive processes proved difficult, though not impossible in principle. Moreover, the notion of "likelihood" of events or "ranking" of uncertainties was difficult to use in the context of a deterministic safety approach.

The perspectives for future work will focus on trying to integrate more the different types of uncertainties. For this aim, an important part will be given to "scientific integration", i.e. the presentation and modelling of the evolution of the repository, both expected and altered, in a global and coherent manner. A unit dedicated to this particular objective was created inside the scientific division of Andra, as a feedback from the organisation of the production of dossier 2001. The quality assurance procedures governing the choice of data will be both strengthened and simplified.

The analogy between uncertainties and risks will be maintained in the next dossier, but Andra's aim is to treat them in a different way. AQS will attempt to analyse each uncertainty systematically through design, modelling and evaluation of residual risk. First of all, for each uncertainty, the analysis will evaluate if the design of the repository manages to reduce the probability or the gravity of the underlying "risk". If it appears possible, then the remaining uncertainty will be considered as part of the normal evolution of the repository and represented within the models dedicated to the safety assessment. If not, either because the potential gravity is significant (for example: a deep borehole in the repository) or because it prevents the performance of an important safety function (for example: uncertainties on the reliability of sealings) the "residual risk" will be evaluated by reference to one of the altered scenarios that will be specifically assessed. Methods for the formalisation of these three stages of the analysis are under development.

This leaves aside the question of how to evaluate the gravity of a residual risk, when there is little reference in the French regulation to dose constraints under altered evolutions, other than a request that the impact should "*be maintained well below levels liable to give rise to deterministic effects*". This is made all the more difficult since a scenario is not always meant to represent a plausible situation, but is designed to encompass various situations that are sufficiently similar. If the probability of a particular situation can be defined, if not always calculated, it can be much more difficult for a whole scenario. "What if" scenarios, not meant to represent a realistic situation but meant to test the robustness of the design, pose a similar problem. In spite of these difficulties, some idea of the likelihood of the corresponding situations will have to be obtained in order to evaluate the relative gravity of a scenario.

Probabilistic calculations, using in particular Monte Carlo distributions, will be performed for the sensitivity calculations of at least the normal evolution scenario. They will not aim at evaluating risk as an indicator, but at gaining access to the relative importance of parameters in a given situation. Those calculations will be performed for the first time in Andra in the context of a safety assessment; the deterministic nature of the safety evaluation as a whole will nevertheless be preserved.

TREATMENT OF UNCERTAINTY IN THE US DEPARTMENT OF ENERGY'S YUCCA MOUNTAIN REPOSITORY TOTAL SYSTEM PERFORMANCE ASSESSMENT (TSPA)

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Abstract:

The regulatory requirements being addressed in the US geological repository programme for spent nuclear fuel and high-level waste specify that performance assessment is to be used to address probabilistically defined mean-value dose constraints. Dose was chosen as the preferred performance measure because an acceptable dose limit could be selected through the regulation-setting process, based on a defined acceptable risk. By setting a dose limit, arguments about the conversion of a potential dose to a potential risk was taken off the table as a potential licensing issue. However, the probabilistic approach called for actually delivers a "risk of a dose," a risk of a potential given dose value to a hypothetical person living at a set distance from the repository, with a set lifestyle, between the time of permanent closure and 10 000 years. Analyses must also be shown for the peak dose if it occurs after 10 000 years, essentially to a million years. For uncertain parameters that are important to system performance, the goal is to present an analysis that, in accord with applicable regulation, focuses on the mean value of the performance measure but also explores the "full range of defensible and reasonable parameter distributions". . . . System performance evaluations should not be unduly influenced by . . . "extreme physical situations and parameter values." These disclosure requirements are to be met by showing a range of potential outcomes and designating the mean value within that range.

Introduction

Uncertainty in a regulatory context

In its review of US Department of Energy (DOE) work leading up to the License Application (LA) that requests authorisation to construct a repository, the US Nuclear Regulatory Commission (NRC) has identified issues that need to be addressed by the DOE before and in the LA. These issues are documented in an Issue Resolution Status Report published by the NRC [1] using Key Technical Issues as organisational categories with sub-issues attached to them. Each Key Technical Issue sub-issue was evaluated by the NRC in terms of information needed to reach closure. Where additional information was needed to allow closure, agreement was reached between the DOE and the NRC regarding the nature of that information to be provided. Appendix A of [1] gives a complete listing of these agreements. There are five agreements relating to Total System Performance Assessment (TSPA) uncertainty (issues TSPAI 3.38, 3.39, 3.40, 3.41, and 4.01). Collectively, as summarised in [2], these issues call for the DOE to:

1. Develop guidance for a systematic approach to developing and documenting conceptual models, model abstractions, and parameter uncertainty.

2. Implement the guidance leading to an improved and consistent treatment of alternative conceptual models, model abstractions, and parameter uncertainty.
3. Write TSPA-LA documentation that reflects the written guidance.

"Uncertainty in a probabilistic context

The reason for using a probabilistic safety assessment approach is to allow the evaluation of a complex system over ranges of independently and dependently varying parameter space. It is also to allow the safety evaluation to include not only those varying parameter spaces, but to also include alternative models, in some cases, and uncertain initiating events that can lead to changes in conditions and pull in new models and varying data sets.

Probabilistic approaches provide a convenient way to evaluate all of the above. Such evaluations are not easily approachable using non-probabilistic methods if the system is very complex. Apostolakis [3] also adds that a benefit of using the probabilistic approach properly is to identify and thus be able to evaluate, "the complex interactions between events/systems/operators."

"Operators" is a specific reference to the subject at hand in Apostolakis' paper, which is the safety of reactor and other active systems. But the equivalent of the operator in the case of a repository may be the preclosure errors in manufacturing of waste packages and package emplacement that can have consequences after system closure. An example of including postclosure consequences from such preclosure errors will be given below."

Apostolakis reminds readers that the integration needed for a probabilistic risk assessment to be meaningful is a good thing, and that its focus is on the inclusion of uncertainty in a quantitative manner. The results should be carefully and also independently reviewed, and may then be used to judge the relative importance of features, events and processes that contribute significantly to risk.

One of the main purposes of a TSPA is to provide decision makers with a meaningful display of the impacts of uncertainty on our understanding of the future behaviour of the system. It is widely understood that uncertainty is unavoidable, but it must be understood and managed.

Because TSPA supports regulatory analyses, decisions about the treatments of accuracy and uncertainty have a regulatory component. In fact, in the US, regulations require the safety assessment to be probabilistic. According to the NRC, TSPA "estimates the dose incurred by the reasonably maximally exposed individual, including the associated uncertainties, as a result of releases … weighted by the probability of their occurrence" (10 CFR 63.2). [4]

Uncertainty and recent TSPA reviews

Internal [5] and external [6,7,8,9] (including international [10] and regulatory [1,11]) reviews have suggested there was inconsistent treatment of uncertainties across disciplines feeding into the TSPA supporting the Site Recommendation. As part of the response to the suggestions made, especially those made by the Nuclear Regulatory Commission (NRC), an "Uncertainty Analysis and Strategy" [11] document was prepared, and it, in turn, was followed by a "Guidelines" [2] document. These guidelines are currently being implemented as part of the preparation of the License Application (LA).

A criticism from several reviewers of the TSPA approach, in addition to but also related to the uncertainty-treatment criticisms, has been its conservative nature. One way to manage uncertainty is to assume bounding values and evaluate the system using those values. This allows demonstration of compliance with post-closure performance requirements. However, it can interfere with an evaluation of the level and the likelihood of risk, and thus allows no quantification of a safety margin. Although a safety margin is a desirable quantity to understand, it is not required by the applicable regulations.

The external reviewers who suggested there was undue conservatism in the TSPA supporting the Site Recommendation were not making a surprising statement. When preparing a TSPA, analysts are faced with competing and contradictory demands. In principle, conservatism is incompatible with a full uncertainty analysis because it obscures understanding. Hence, it should be avoided. In practice, however, the use of conservative or bounding approaches is a normal reaction to the absence of definitive information. Conservatism is a recognised approach to dealing with uncertainty.

The TSPA analysts may be asked to make conservative assumptions, even if more realistic understanding is potentially available, in order to simplify tests, models, or analyses. This, of course, is related to reducing cost (and schedule, which has a direct impact on costs). It can be said that if a conservative analysis shows safety, there is an enhancement of confidence in the likelihood of safety. So, reality steps into the ideal world and conservatism will be part of any complex system analysis, and may therefore obscure and perhaps even skew uncertainty analysis results. This makes it incumbent on the analysts to evaluate the impacts of conservatism. These impacts should be understood and explained.

Partly in response to these and other external and internal criticisms, the goal for TSPA for several years has been to deliver a more realistic, less bounding, analysis. Conservatism that remains must be identified and evaluated in terms of its basis and importance. A more realistic treatment of uncertainty in the TSPA is not the same thing as obtaining a full understanding of realistic performance, however. Full understanding where large spatial and time scales are involved for a complex system may be forever out of reach, but the goal is to provide a ‘reasonable expectation’ of safety, not complete certainty.

Progress has been made in changing several dozen conservative, fixed-value data points into simplified models that are being used and evaluated. Scientists and performance assessment analysts are organised to work together as teams to incorporate, propagate and evaluate uncertainty in models and parameter distributions.

Documentation is required to give a clear, traceable explanation of what was done. Documentation alone cannot explain a process, however, the process itself must be outlined and demonstrably followed to assure consistency in approach. The process for selecting parameter values and distributions for TSPA is a formal one that uses specialty teams to strongly integrate scientists, designers, engineers, and performance assessment analysts.

Responses to reviews: Uncertainty strategy and guidelines

Summary of uncertainty analyses and strategy document [11]

The strategy, it almost goes without saying, is to develop a TSPA that meets the regulatory intent of providing the basis for a finding of a “reasonable expectation” of safety by the regulator. This requires the TSPA to document the quantified uncertainties in inputs to the performance assessment. In order to meet this requirement, however, there must be a clearly defined process in place that encourages the quantification of uncertainties and gains concurrence on the process approaches with the NRC.

The technical basis for all uncertainty assessments must be provided, addressing conceptual model as well as parameter and initiating event uncertainty. The use of "bounds" and "conservative" estimates is unavoidable, but should be clearly identified, explained and evaluated. The purpose is to develop and communicate uncertainty information that can be used by decision-makers.

In order to assure this strategy is properly implemented, the DOE developed detailed guidelines for implementation.

Uncertainty strategy guidelines [2]

The strategic goal is an analysis approaching realism. Pragmatically, however, some conservatisms must remain. The documentation needs to be clear about where they are, what their basis is, and what their impacts are.

The focus of the assessments should be on providing a realistic treatment of uncertainty, which is not the same as a full understanding of realistic performance. Simplified models are acceptable in the TSPA, and are not necessarily conservative, though they may be.

Broad uncertainties need to be justified and explained, and analyses need to show they do not contribute to an unwarranted risk dilution [10]. Risk dilution may occur when, in order to capture incomplete understanding, analysts broaden probability-density-functions (pdfs) unduly to assure they are being conservative. When overly broad pdfs are sampled in a complex probabilistic analysis, however, they can introduce unduly small (or unduly large) numbers into the performance-measure averaging process, and they can affect the time of the occurrence of releases for the regulatory performance measure. The net effect may be non-conservative, and needs evaluation. Scientists and analysts must work together to properly and defensibly incorporate uncertainty in TSPA models and parameter distributions. In their documentation they must focus on clear explanations of what was done in their mathematical and conceptual descriptions. Traceability, meaning a transparent linking to the supporting technical basis, has to be provided.

Status of guidelines implementation

The guidelines document addresses the consistent treatment of abstractions in TSPA, of alternative conceptual model uncertainty, and of parameter uncertainty. It also addresses the propagation of risk through the abstraction processes that lead to simplified models.

The guidelines document addresses Nuclear Regulatory Commission (NRC) Key Technical Issue agreements related to uncertainties, point for point.

Implementation is to be documented in Analysis and Model Reports (AMRs) currently being updated for License Application (LA) that is to be submitted late in 2004.

Approach to consistency for implementation of uncertainty guidelines

As Apostolakis [3] noted, human errors, whether they occur in software or hardware production, is an issue not easily treated in a probabilistic risk assessment. The Quality Assurance programme has rigorous reviews of the software and configuration management issues, but a problem arises when a complex organisation integrates itself to produce an integrated safety assessment. It turns out when scientists and engineers meet to feed the TSPA modellers that: (1) definitions were not interpreted the same way and measures and uncertainties generated are not compatible with the needs of the analysts, (2) assumptions that bridge disciplines were incompatible, (3) uncertainty propagation, even where uncertainties were properly treated, is not easy. To bridge this set of potential gaps before it becomes a last minute emergency, the guidelines document, not unlike a Quality Assurance procedure, identifies those who are responsible for seeing that these things are prevented to the extent practicable, or handled expeditiously when they occur.

The following individuals are identified in the document, with their duties:

1. Parameter Team Lead (PTL) – Leads the process for ensuring the consistent treatment and documentation of parameter values, parameter distributions, and parameter uncertainty.
2. Abstraction Team Lead (ATL) – Leads the process for ensuring the consistent treatment and documentation of alternative conceptual models and model abstractions.
3. Subject Matter Expert (SME) – Identifies and develops alternative conceptual models, model abstractions, and parameters consistent with guidelines (personnel most knowledgeable about individual process models and uncertain parameters).
4. Process Modeller – Assists the SME in developing and implementing process models and abstractions (where appropriate) for use in the TSPA-LA.
5. TSPA Analyst – Integrates alternative conceptual models and model abstractions in the TSPA-LA model.

Types of uncertainty, and approaches to their evaluation and management

Parameter uncertainty

Formal processes are used for selecting parameter values and distributions for TSPA. The effort involves identification and categorisation of the TSPA parameters. For uncertain parameters that are important to system performance, the goal is to represent, as the regulations require, rightfully: the "full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values."

Uncertainty distributions are developed considering available data. The use of the parameter in the TSPA model (e.g., scaling issues, variability, application in model) is considered in developing descriptions of uncertainty. Distributions are developed jointly by subject matter expert, PA analyst, and a statistician. Parameter distributions that fold in the agreed on uncertainties are implemented in TSPA through a controlled database.

Alternative conceptual models (ACMs)

For each process of interest, an attempt is made to identify ACMs (if any) consistent with the available information. If only one conceptual model is consistent with all information, ACM uncertainty is not significant. The approach for identified multiple ACMs is to evaluate impacts of alternatives on the appropriate subsystem or component performance. If ACMs result in the same subsystem performance, ACM uncertainty is not significant.

If two or more ACMs show different subsystem performance, then the principal investigators must develop abstractions for both and deliver the to the TSPA analysts.

If abstractions for ACMs are not straightforward, conservatism is an option. TSPA evaluates system-level impact of ACMs. If impacts are significant, options are to carry multiple ACMs in TSPA with weighting, or to consider a conservative choice between ACMs. The latter has typically been the approach to dealing with ACMs in Yucca Mountain TSPAs.

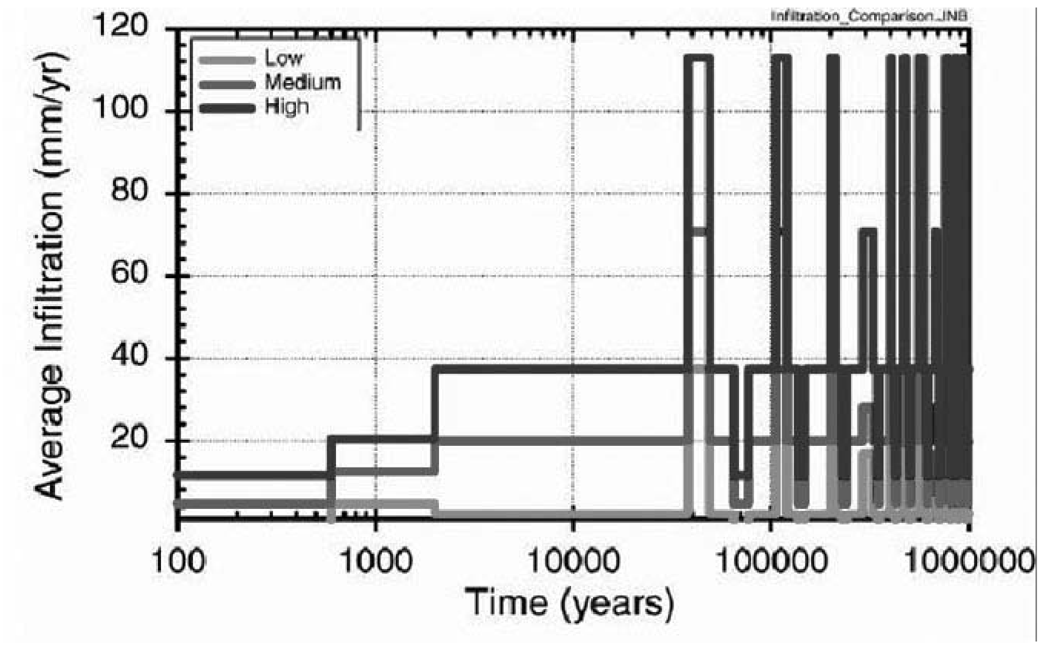
Abstraction

The key to the proper incorporation of process-level uncertainties lies in the formulation of the abstractions. Their goal is to capture aspects of process model important to system interactions, with appropriate representation of uncertainty. They are developed by subject matter experts, and reviewed by TSPA analysts.

Various forms of abstraction to capture the salient features of the process-level models are acceptable; e.g., simplified numerical models, simple functions, response surfaces, and parameter distributions. The abstracted models are implemented by TSPA analysts, and again reviewed by subject matter experts.

An example of an abstraction that also illustrates parameter and ACM uncertainty treatment is the use of a stylised step-wise introduction of successive climate states that are, admittedly, conservatively selected from the potential progression into the future. Infiltration uncertainty is then added realisation by realisation by sampling from three possible infiltration ranges for each climate state: a low range that has a 17% likelihood, a medium range that occupies 48% of the probability space, and a high case that may occur 35% of the time. The outcome is a set of flow-fields illustrated in Figure 1. Given a certain point in time, the climate-state is fixed, however, the water infiltration rate may vary widely, reflecting the uncertainty obtained from field, laboratory and analogue studies. The result is shown in Figure 1.

Figure 1. **Unsaturated Zone Flow Fields: 13 distinct flow fields account for uncertainty in future climate states and infiltration into the mountain (using 3 climate states before 10 000 years, and 4 after, all overlain with three infiltration-rate states indicated by the three colors, both alternative conceptual model and parameter uncertainty are addressed) [12]**



Initiating Event Probability Uncertainty

A probabilistic analysis allows the incorporation of events that are unlikely and may lead the TSPA to reach for sub-models not used if the event does not occur. The key to selecting this other set of sub-models is the frequency or likelihood of occurrence. Such likelihoods are usually, and properly, determined through internal or external expert judgement based on the analysis of analogous systems, or on formal expert elicitation using internal, external, or both types of experts.

An example of expert-judgement based designation of an event probability, and a formal expert-elicitation based evaluation of another probability, will be illustrated below.

Premature Waste Package Failure Example

A non-mechanistic (expert-judgement based) early (at emplacement) waste package failure probability was included in the model to avoid the non-conservative choice of not addressing the probability of such failures for lack of a mechanistic model. The experts consulted the failure rates of roughly comparable manufactured entities and came up with the following failure probabilities for use in TSPA. Note that the expected case has from zero to two failures.

Figure 2. **Expert-judgement based estimates of failure-at-emplacement probability for waste packages [13]**

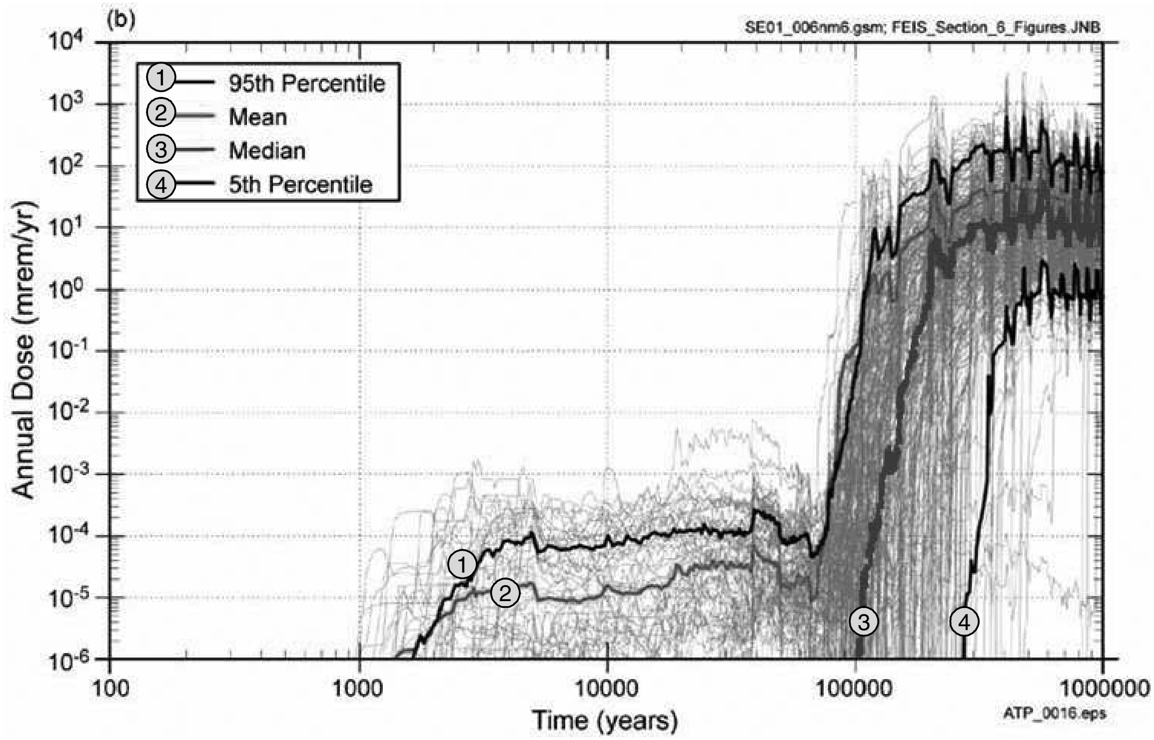
Number of Packages	Probability
0	0.77
1	0.2
2	0.027
3	2.30E-03
4	1.50E-04
5	8.00E-06

The results are shown in Figure 3. Prior to incorporating these early failures, there was no dose consequence above 10^{-6} mrem/year during the first 80 000 years.

Probabilistic Volcanic Hazard Analysis (PVHA) Example

The PVHA study was done to develop a defensible assessment of the volcanic hazard at Yucca Mountain, with quantification of uncertainties [14]. It utilised eight experts, seven of them external to the project, in a formal expert elicitation. Twenty years of geologic exploration work provided a basis for each expert making quantitative estimates of model and parameter uncertainty. Expert elicitation, in turn, allows the quantitative assessment and incorporation of alternative models and parameter values suggested by these experts.

Figure 3. **Example preliminary TSPA results with premature waste package failures probabilistically included [13]**



The types of alternative models considered for an igneous event were both temporal (when) and spatial (where) models. There were two alternative temporal models: (1) homogeneous Poisson models, and (2) several non-homogeneous models, namely, volume-predictable, waxing or waning models.

Similarly there were alternative spatial models of the homogeneous and non-homogeneous type. The homogeneous models were locally homogeneous "source zones," defined by observed volcanoes, structural control, geochemical affinities, tectonic provinces, etc.

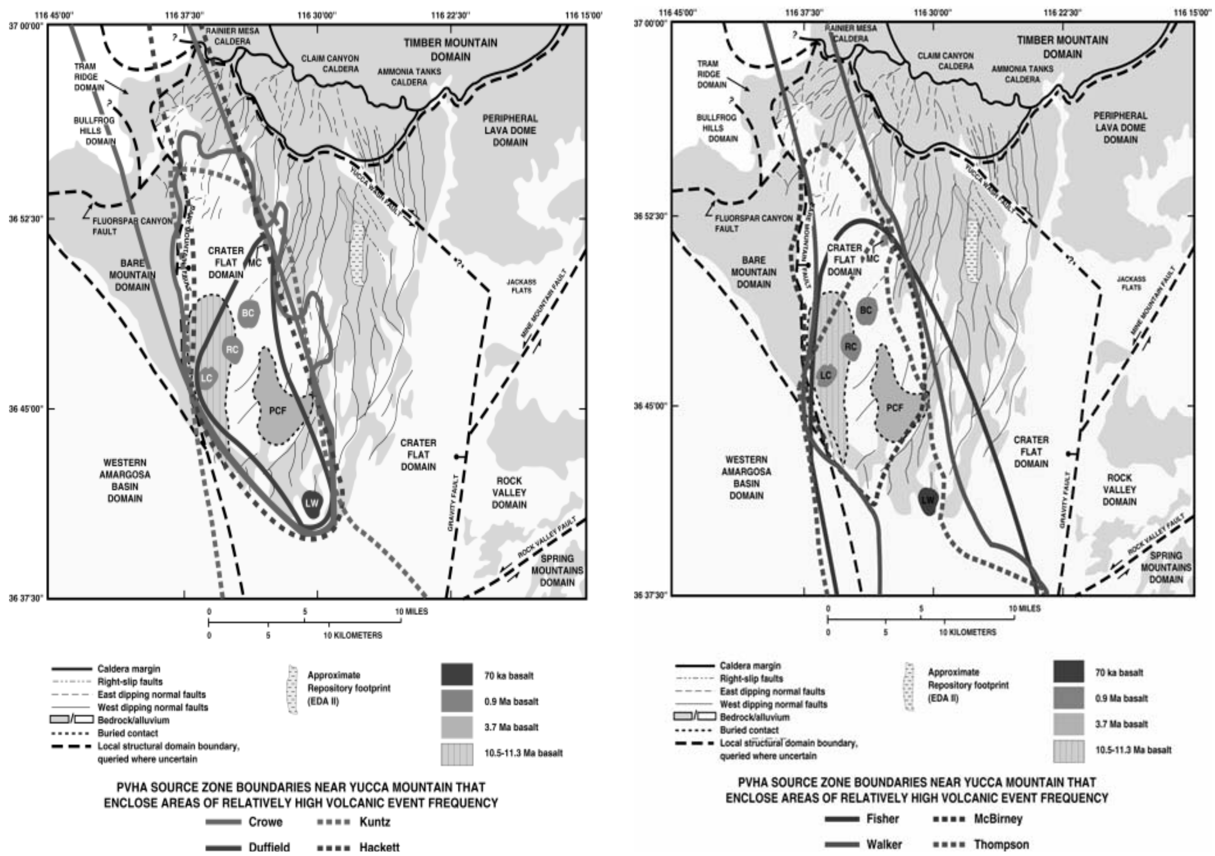
The non-homogeneous models were either parametric (bivariate Gaussian distribution for the field) or nonparametric (kernel density function and smoothing operator).

The point being that the alternative models and data ranges associated with them were treated, through the mathematics of the expert-elicitation process, in such a way as to allow for one distribution of annual frequencies of a dike intersecting the repository.

The experts each drew contours on a map suggesting where they believed the zones of higher potential eruptive frequency were. The next two illustrations (Figures 4 a and b) give the results of that exercise.

Figure 4: **Eight experts' interpretations of the zone boundaries near Yucca Mountain with relatively high volcanic event frequency [14]**

(a) **(b)**



The uncertainty in the frequency of potential eruptions in the repository area were evaluated using an event tree (Figure 5). The report in which these results are presented [14] explains the logic and mathematics underlying this event tree. The important point to be made here is that the uncertainty attributed to models and parameters by the experts was propagated through this tree to result in estimates of a dike intersecting a repository. One conceptual model (Figure 6) was used to allow each expert to calculate the frequency of dike propagation leading to an intersection with the repository in terms that would be compatible with the results of every other expert's calculation. This allowed acknowledged and quantified uncertainty to be propagated forward to the final result to be supplied to the TSPA analysts (Figure 7).

Figure 5. **Event tree used to incorporate conceptual model and parameter uncertainty into the probability of a dike intersecting the repository [14]**

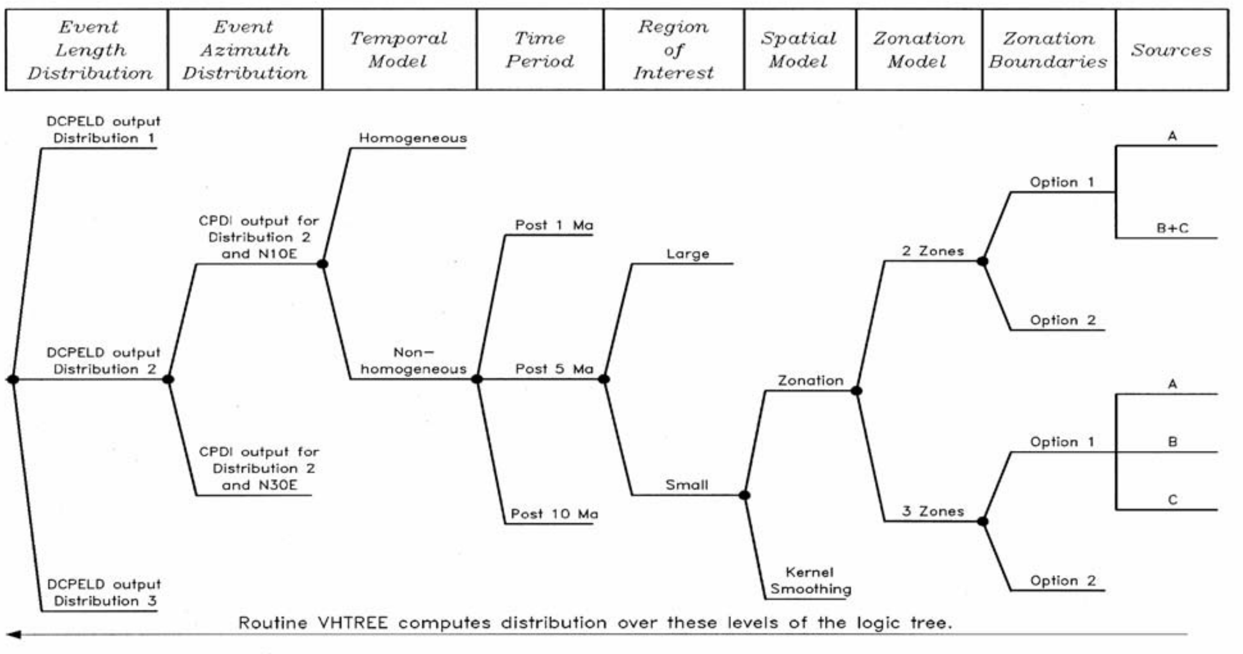


Figure 6. **Model for calculating probability of propagating dike intersecting with repository [14]**

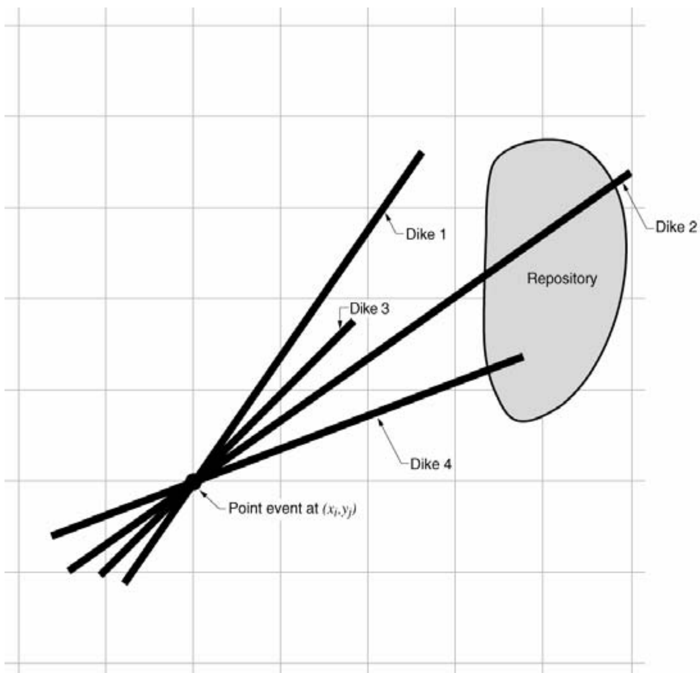
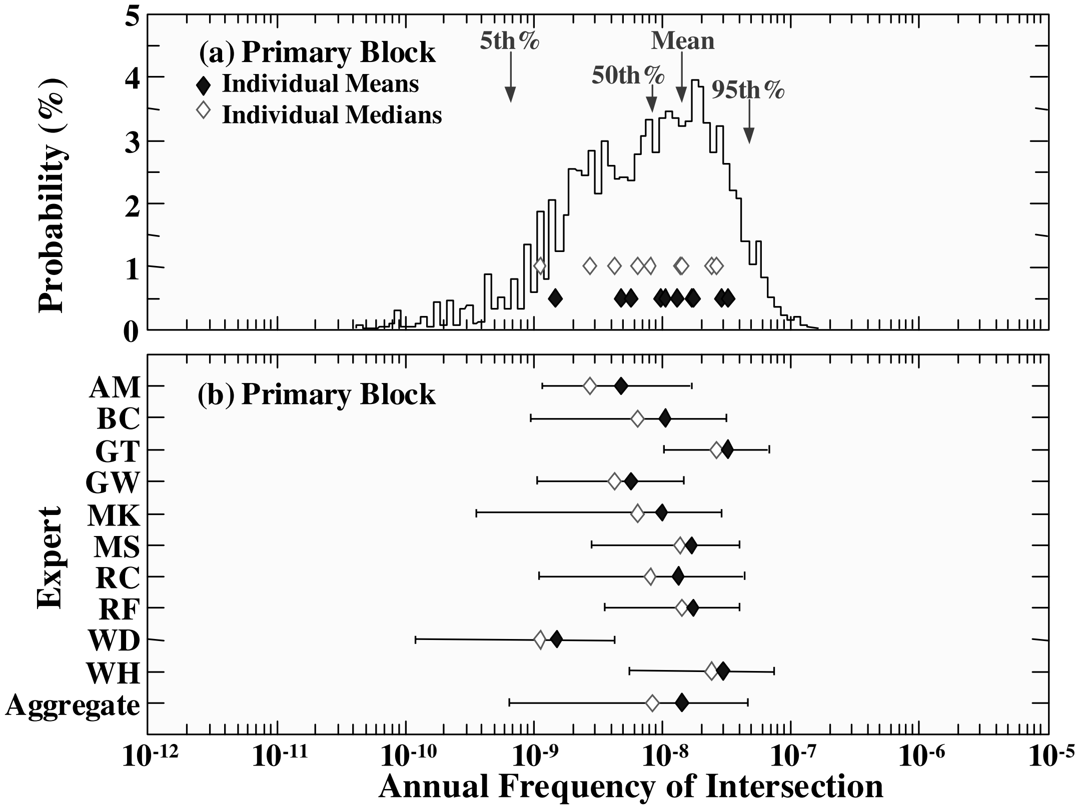


Figure 7. **Annual frequency of intersection results of PVHA used as input to the TSPA analysis [14]**



The PVHA expert elicitation was conducted to assess the volcanic hazard, with particular focus on quantifying uncertainties in the frequency of a dike intersecting the repository. This is a requirement if one is to estimate a probability-weighted dose as a decision-aiding performance measure.

The full range of temporal and spatial probability models was used to characterise potential future volcanic occurrences. The PVHA output provided hazard frequencies and event descriptions that served as inputs to consequence models. The consequence models, in turn, were able to propagate the uncertainty from the PVHA along with uncertainties in the consequence models themselves. The output of such an analysis is given in Figure 8. This result is from was an older analysis, since superceded. Hence it is not a reflection of what is expected for the TSPA-LA

Figure 8 shows 500 out of 5 000 TSPA realisations. It highlights the 95th, 50th, and 5th percentiles and the mean annual dose, weighted by probability. The initial, smoother portion of the curve rises and then falls. It rises with the increasing number of realisations that include a dike intrusion, which increases with time. After about 400 years the curve falls because of radioactive decay, which offsets the rise in probability-weighted doses from intrusions. Where the graph becomes more uncertain is where groundwater radionuclide transport from waste packages disrupted by the magma begins to arrive at the biosphere. Note that some of the very high potential dose values skew the mean to temporarily rise above the 95th percentile.

Figure 8. **Uncertainty in TSPA probability-weighted dose results from igneous events resulting in dikes intersecting the Yucca Mountain repository [12]**

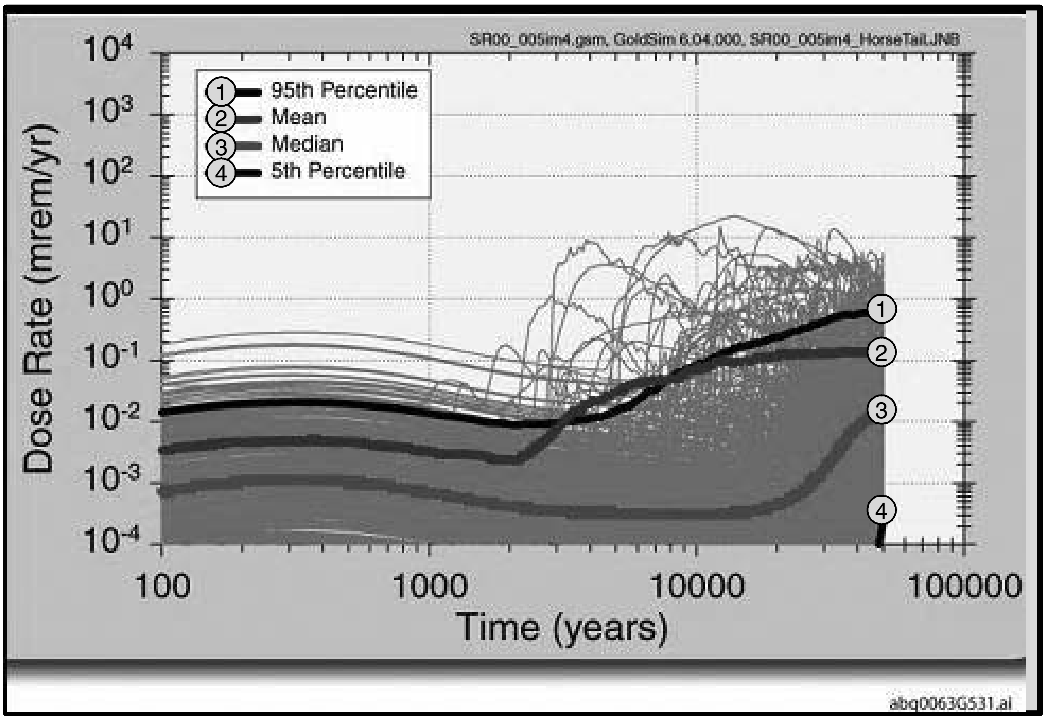
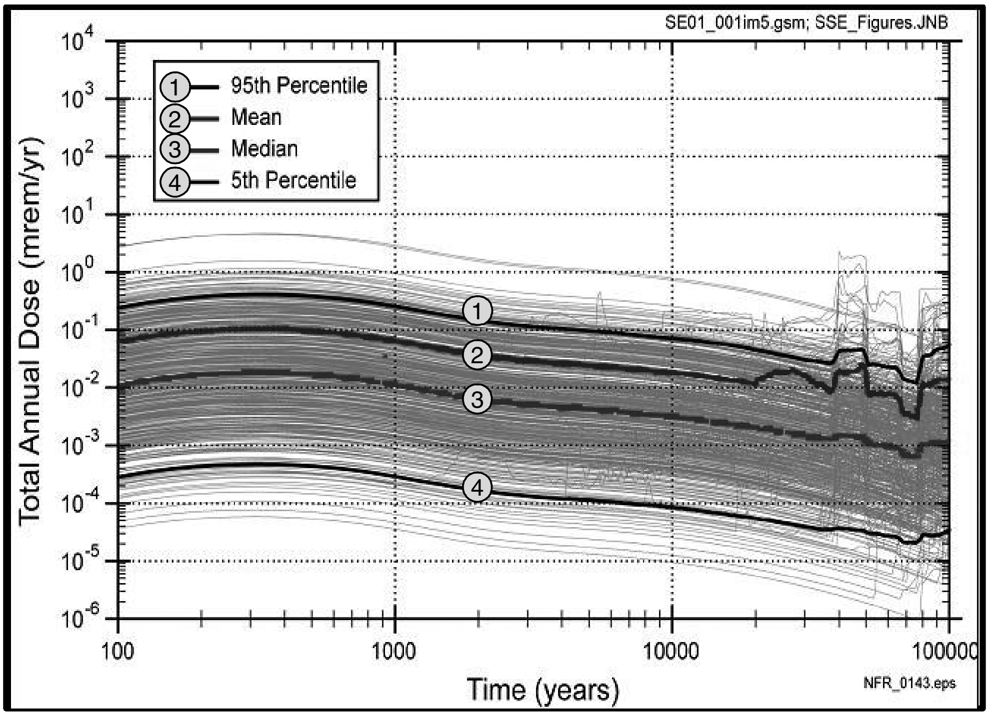


Figure 9. **Recalculation of potential probability-weighted doses from dike intersections with a potential repository at Yucca Mountain (change in consequence model, not probability model) [15]**



A difficulty in explaining this type of result to a non-specialist audience lies in the use of a probability-weighted, rather than a disaggregated, dose. The difficulty in explaining a disaggregated dose, however, lies in the natural discounting of the very low probability and focusing instead on the high potential-dose consequence.

Figure 9 shows a recalculation, using the same PVHA frequency-of-intersection input, but using a refined consequence model. The point of importance to this discussion is that the final judgement of safety, whichever model is selected for that crucial calculation, needs to be supported by a thorough analysis of uncertainties, their sources, and propagation.

Conclusions

Confidence in the treatment of uncertainty in TSPA comes from understanding uncertainty in underlying data, models, and parameters. Therefore, analyses such as those just illustrated need to be accompanied by documentation of the propagation of uncertainty through the TSPA.

Importance of specific uncertainties in underlying information depends on the measure of interest. Sensitivity analyses show that many uncertainties don't really matter to system performance. Regulations focus on mean performance, and therefore on accuracy of the estimate of mean performance. Uncertainty in model results is readily quantified once models and input distributions are complete, and provides insight into model behaviour and system understanding.

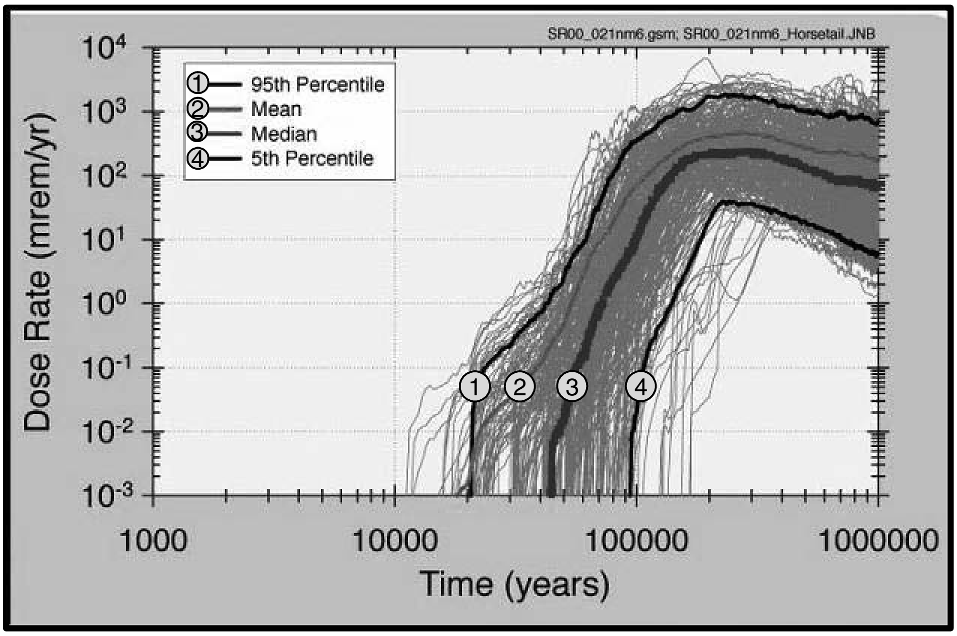
A final observation: does uncertainty always increase over time? No, not always for all systems.

For some systems, such as the older analysis illustrated in Figure 10, uncertainty will reach a maximum and then decrease as the occurrence of the controlling processes (e.g., waste package degradation in this example) becomes more certain. After that point in time, however, it is to be expected that remaining natural system processes do become more uncertain over time.

This is illustrated in figure 10 for uncertainty in a system not disturbed by igneous events. Please note that Figure 10 is an earlier analysis than that shown in Figure 3, and includes differences in assumptions, models and data. It is being used here to illustrate a point about uncertainty over time only. The quantified uncertainty is reflected in the vertical extent of the "horsetail" plot at any given point in time. Results become less uncertain as engineered system containment is lost, which is highly uncertain in this analysis. Thereafter, uncertainty increases again.

The engineered system uncertainty is coupled with natural system uncertainty on the left side of the diagram, with engineered system uncertainty dominating, until about 200 000 years. Thereafter, it is natural system uncertainty that is reflected in the results from 200 000 years to a million years, and that uncertainty expands gradually over time as is to be expected. One reason the engineered system uncertainty is large is that it is a transient system, it changes in important ways over time. By contrast, the natural system is modelled as a series of steady states. Transient system uncertainties tend to be larger than steady-state uncertainties, especially when plotted on a log scale versus time.

Figure 10. **A preliminary "horse-tail" plot folding in all quantified uncertainties for a preliminary Yucca Mountain repository TSPA in which disruptive events were not included [12]**



References

[1] USNRC (2002), *Integrated Issue resolution Status Report,* NUREG-1762, Washington, D.C., U.S. Nuclear Regulatory Commission.

[2] BSC (Bechtel SAIC Company) (2002), *Guidelines for Developing and Documenting Alternative Conceptual Models, Model Abstractions, and Parameter Uncertainty in the Total System Performance Assessment for the License Application.* TDR-WIS-PA-000008 REV 00 ICN 01, Las Vegas, Nevada.

[3] Apostolakis, G.A. (2003), "How Useful is Quantitative Risk Assessment?" Massachusetts Institute of Technology, Engineering Systems Division, Working Paper Series ESD-WP-2003-05, available at http://esd.mit.edu/WPS/wp-2003-05.pdf.

[4] USNRC (2002), *Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, NV.* 10 CFR Part 63, Washington, D.C., U.S. Nuclear Regulatory Commission.

[5] YMP (Yucca Mountain Site Characterisation Project) (2001), *Evaluation of Uncertainty Treatment in the Technical Documents Supporting TSPA-SR*, Las Vegas, Nevada.

[6] Budnitz, B., R.C. Ewing; D.W. Moeller, J. Payer, C. Whipple and P.A. Witherspoon (1999), *Peer Review of the Total System Performance Assessment-Viability Assessment Final Report.* Las Vegas, Nevada: Total System Performance Assessment Peer Review Panel.

[7] Hornberger, G.M. (2001), "Documented Findings of the Advisory Committee on Nuclear Waste's (ACNW's) Vertical Slice Review of the TSPA-SR." Letter from G.M. Hornberger (U.S. Nuclear Regulatory Commission) to R.A. Meserve (U.S. Nuclear Regulatory Commission), September 18, 2001.

[8] NWTRB (U.S. Nuclear Waste Technical Review Board) (2001), *Report to the U.S. Congress and the Secretary of Energy, January to December 2000.* Arlington, Virginia.

[9] Cohen S. & Associates (1999), *Review of Total System Performance Assessment in the U.S. Department of Energy Viability Assessment for the Yucca Mountain Site.* [Las Vegas, Nevada]: Clark County, Nevada, Department of Comprehensive Planning.

[10] OECD/NEA-IAEA (2002), *Joint International Peer Review of the Yucca Mountain Site Characterization Project's Total System Performance Assessment Supporting the Site Recommendation Process*. Paris, France: Nuclear Energy Agency.

[11] BSC (Bechtel SAIC Company) (2001), *Uncertainty Analyses and Strategy.* SA011481M4 REV 00. Las Vegas, Nevada.

[12] CRWMS M&O (2000), *Total System Performance Assessment for the Site Recommendation.* TDR-WIS-PA-000001 REV 00 ICN 01. Las Vegas, Nevada.

[13] DOE (U.S. Department of Energy) (2001), *Yucca Mountain Science and Engineering Report.* DOE/RW-0539. Washington, D.C., U.S. Department of Energy, Office of Civilian Radioactive Waste Management.

[14] CRWMS M&O (1996), *Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada.* BA0000000-01717-2200-00082 REV 0, Las Vegas, Nevada.

[15] BSC (Bechtel SAIC Company) (2001), *Total System Performance Assessment – Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain – Input to Final Environmental Impact Statement and Site Suitability Evaluation*. REV 00 ICN 01, Las Vegas, Nevada.

RISK CONSIDERATIONS IN THE DOMAINS OF PROTECTIONS AGAINST MAJOR ACCIDENTS IN COMPARISON WITH RISK CONTROL FOR NUCLEAR POWER PLANTS

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Abstract

Risk-based decision making in the control of major chemical hazards in Switzerland is presented and compared with new risk-based decision-making framework for Swiss nuclear power plants. The legal framework on which risk control of major chemical hazards is based in Switzerland is provided by article 10 of the “Law Relating to the Protection of the Environment” (LPE, 1983) which deals with protection against disasters. Enforcement is based on the Ordinance on “Protection against Major Accidents” (OMA, 1991) which was put into effect on April 1, 1991. OMA reflects well-established procedures in risk control, in particular those used in the Netherlands in the context of the environmental control policy. At the same time, OMA requires implementation of state-of-the-art safety technology in agreement with the German practice. It is compatible with the corresponding regulations of the European Union (EC Directive 96/82 [1996] and EC Directive 90/219 [1990]). Risk analysis and risk-informed decision making have a long tradition in the licensing and supervision of nuclear installations. Consequently, the new Swiss nuclear legislation that will come into force in 2005 makes explicit reference to risk. The Nuclear Energy Ordinance, the implementation rules for the Nuclear Energy Act, contains quantitative risk criteria for the safe operation of existing nuclear power plants and for the licensing of new ones. A preliminary outline of the decision-making scheme for risk control, to be published in the Regulatory Guides of the Swiss Nuclear Safety Inspectorate (HSK), is presented. The decision-making approach is then compared to the one used for the control of major chemical hazards. Finally, the paper contains some reflections on the use of risk-based regulatory approaches from the point of view of nuclear waste disposal.

The opinions expressed in this workshop paper are those of the authors.

Keyword

Risk control, decision making, quantitative risk criteria, chemical hazards, nuclear power plant

Introduction

The legal framework on which risk control is based in Switzerland is provided by article 10 of the “Law Relating to the Protection of the Environment” (LPE, 1983) which deals with protection against disasters. In the aftermath of the fire of November 1, 1986 in Schweizerhalle near Basel with the subsequent catastrophic pollution of the Rhine river, political pressure increased to improve provisions on protection against serious damage resulting from major accidents. As a consequence, the

Ordinance on "Protection against Major Accidents" (OMA, 1991) came into force on April 1, 1991. The issues of concern are the protection of the population, surface and ground water, soil and property. Other issues of concern may arise in special cases such as the protection of natural parks, livestock, recreational areas or ecosystems of particular value. The most important stakeholders took part in the process of creating the draft version of the OMA (chemicals industry, transportation companies, Swiss railways, future regulators etc.). In addition, before an ordinance becomes law, all affected stakeholders are consulted by the government department in charge.

Outline and scope of the OMA

The Ordinance reflects well-established procedures in risk control, in particular those used in the Netherlands in the context of the environmental control policy. At the same time, the OMA requires implementation of state-of-the-art safety technology in agreement with the German practice. The OMA applies to all facilities in which (i) the threshold quantities for a defined set of substances are exceeded (examples of threshold quantities are 200 kg of chlorine, 2 000 kg of ammonia, 20 000 kg of liquefied petroleum gas or 200 000 kg of petrol) or in which (ii) dangerous natural or genetically modified micro-organisms are being contained. Furthermore, OMA applies to (iii) transport routes used for the shipping of dangerous goods (railway lines, roads, and Rhine river).

Terminology

The OMA provides the following definition for "hazard potential" and "risk":

- Hazard Potential means the sum of all the consequences which substances, products, special wastes, micro-organisms or dangerous goods could have as a result of their quantity and properties.
- Risk shall be determined by the extent of the possible damage to the population or the environment, caused by major accidents and by the probability of the latter occurring.

Note that risk is defined merely as a function of damage extent and probability of occurrence. The mathematical relationship between these two parameters is not specified.

Procedure

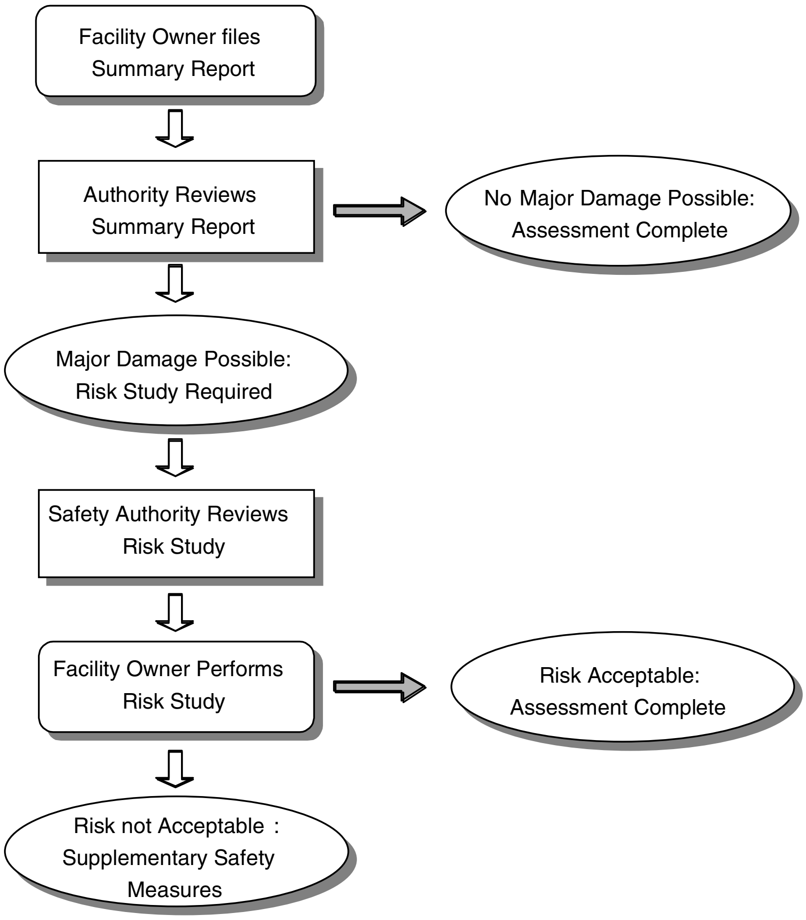
The procedure to control and assess relevant hazard potentials and risks consists of two steps (Figure 1).

In the first mandatory step, the owner of a facility submits a *summary report* containing an assessment of hazards. On the basis of the hazard assessment in the summary report, the enforcement authority decides whether, in a second step, a *quantitative risk assessment* has to be performed.

The summary report with the hazard assessment contains the following main items:

- A list with the maximum amount of any potentially hazardous substance kept at the facility at any given time and for which the threshold value specified by the OMA is exceeded.
- A detailed description of existing safety measures.
- An estimation of the extent of possible damage to the public and the environment resulting from major accidents at the facility, regardless of the (un-)likelihood of the accident(s) (maximum probable loss, see also section 3.3).

Figure 1. **Two-step Procedure for hazard and risk assessment for facilities and installations falling under the OMA (SAEFL, 1996a)**



If, in the first assessment step, the enforcement authority concludes that serious damage to the public or to the environment from major accidents must be expected, it orders a *quantitative risk assessment* to be performed. If serious damage is not to be expected, the assessment procedure is completed after the first step. In 1996, when the Swiss Agency for the Environment, Forests and Landscape (SAEFL) began its systematic data collection, some 2 477 facilities in Switzerland were recorded as falling under the OMA. In 40% of all cases, the summary report had been reviewed and classed. For 163 facilities, a risk assessment has been or will be performed (SAEFL, 1996a). The number of about 2 500 installations that fall under the OMA did not change since the first review.

The need for consistency in the application of the OMA throughout the different types of facilities and throughout the different regions of Switzerland was recognised at an early stage. Consequently, the SAEFL published a series of guidance documents for risk analysts and reviewers (i.e. enforcement authorities):

- *Handbooks* with the status of guidelines, explaining the technical hazard and risk assessment process to meet the OMA. In addition, separate guidelines have been published covering the evaluation of the extent of damage and the risk evaluation (SAEFL, 1996c).

- *Manuals*, which are specific to one type of installation (such as liquid gas storage tanks) and which contain detailed technical information on how to perform hazard and risk assessment for that particular installation. Manuals contain technical background information on the physical phenomena involved in the accidents to be analysed as well as a prototype event-tree/fault-tree risk model for a fictitious facility. So far, manuals have been published for LPG storage (Basler & Hofmann, 1992), high-pressure natural gas pipelines (SNCG, 1997) and large oil storage facilities (Carbura, 1999).
- *Case studies* for fictitious facilities. These are reference studies containing models and data meant to be transferred and/or adapted to a similar case involving the same type of facility. Some case studies contain reference computer codes for solving the event-tree/fault-tree models. So far, a case study for liquid petroleum storage facilities has been published (SAEFL, 1996b) and a case study for ammonia cooling units has been drafted (SAEFL, 1999).

The *manuals* and *case studies* of the guidance documentation accompanying the OMA define the state-of-the-art for hazard and risk assessment for a particular type of facility or installation. The fact that the guidance documents are developed in a joint effort by industry and enforcement authorities guarantees a consensus over what should be considered state of the art. If the state of the art changes because technology evolves, the guidance documents have to be revised. The initiative for such revisions can come from industry or from the enforcement authorities.

The risk assessment is used to (i) control the risk level in facilities where major accidents with severe consequences for the population and/or the environment could occur and to (ii) inform the public about existing risks. It is but one element in a strategy aimed at protecting the population and the environment from the consequences of major accidents.

The hazard and risk assessment studies are reported to the enforcement authorities. A digest of each risk assessment study is available publicly on request. The digest contains the main results and findings of the study. The OMA requires an update of the summary report when significant changes occur at the facility. Examples of significant changes are when the production or storage capacity is raised, new equipment is installed or backfitted or when safety-relevant modifications are made to the production and/or storage processes. Based on the updated summary report, the authority decides whether the risk assessment needs to be updated, following to the two-step process described above.

Considerable effort has been put into making the hazard and risk assessment simple and accessible to the facility owners. Still, it is expected that both risk analysts and reviewers (enforcement authorities) be knowledgeable in the principles of quantitative risk assessment. Usually, the owners of facilities contract a specialised engineering firm to perform the risk assessment. There are no requirements for the risk analyst to formally document his or her competence.

Legal/Policy issues

OMA requires the owner of a facility to take all appropriate measures to reduce risk consonant with the state of the art of safety technology and personal experience. Owners must also take all economically viable measures to reduce hazards, to prevent accidents and limit the consequences of possible accidents should they occur. In addition, OMA defines a risk control process described before. The nature of the risk reduction measures (if such measures are necessary) is not prescribed. This is perceived as an advantage, because it allows the owners of facilities to choose between a range of alternative solutions to reduce risk.

Description of summary reports and risk studies

Hazard identification

The *summary report* with the hazard assessment must contain the following main items:

- A list with the maximum amount of any potentially hazardous substance kept at the facility at any given time *and* for which the threshold value given in the OMA is exceeded [note: the thresholds defined are the same as or lower than those of the Seveso-Directive (EC Directive 96/82 and EC Directive 90/219)].
- A description of *safety* measures in place at the facility or installation.
- An estimation of *the* extent of possible damage to the public or the environment resulting from major accidents, regardless of the (un-)likelihood of the accident(s) (maximum probable loss).

Appendix I of the OMA (1991) contains a list of potentially hazardous substances and products. Above all, it contains criteria for the identification of potentially hazardous substances. These include toxicity, ecotoxicity, flammability, explosion hazard as well as criteria for dangerous micro-organisms. If the quantities of substances stored at a stationary facility exceed the substance-specific thresholds of OMA (appendix I), they must be included in the summary report discussed above.

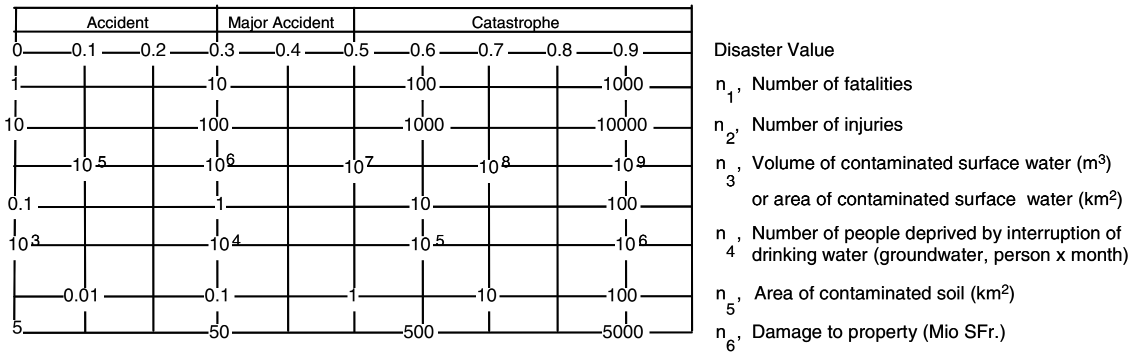
Only those damage indicators relevant to the case at hand need to be assessed (Table 1). For instance, for the three examples appearing in this paper (LPG, chlorine and ammonia), the number of fatalities (indicator n_1) proved to be the only relevant damage indicator.

Table 1. **OMA damage indicators as given in SAEFL (1996c)**

Man	
n_1	Number of fatalities [people]
n_2	Number injured [people]
Natural resources	
n_3	Polluted surface water [m^3 or km^2]
n_4	Polluted ground water [person x months]
n_5	Polluted soil [km^2]
Property	
n_6	Damage to property [SFr]

Figure 2 shows the mapping of damage indicators into the three categories “Accident”, “Major Accident” and “Catastrophe”. If a disaster value of 0.3 is reached or exceeded for any one of the relevant damage indicators, the authority orders the owner to perform and submit a risk study.

Figure 2. **Scale of extent of damage indicators (assignment of disaster values) (SAEFL, 1996c)**



Event scenario assessment

Event scenario assessment generally consists of the following steps:

- Identification of the *main accident scenarios* to be considered for the type of facility. The main accident scenarios are described at the phenomenological level and represent the link to consequence assessment (example: the occurrence of a BLEVE is a main accident scenario considered for LPG storage).
- Description of the *event sequences* associated with the main accident scenarios. These refer to facility-specific events (starting with the causes or initiating events) which must occur for the main accident scenarios to take place (example: a fire under the tank leads to a catastrophic tank rupture, which leads to a large and rapid release of liquefied gas which can trigger a BLEVE). The event sequences are the basis for the fault-tree/event-tree models.
- Modelling of the event sequences with of fault-trees and event-trees. To reduce the complexity of the event tree model (number of event trees, number of event sequences), *functional events* are sometimes defined (in the LPG example below, they correspond to the release categories; in the chlorine and ammonia examples, the functional events coincide with the main scenarios). The frequency of each functional event is calculated with a fault tree.

Event sequences can be identified in a top-down approach by searching for all possible ways to trigger one of the main accident scenarios. Alternatively, a bottom-up approach can be used in which malfunctions are systematically identified and analysed for their potential to trigger a scenario leading to unwanted consequences (FMEA, HAZOP and similar approaches). In practice, the top-down and bottom-up approaches are often used in combination.

As an example, Table 2 lists the main accident scenarios and the corresponding event sequences for the LPG, ammonia and chlorine examples (SAEFL, 1996b & 1999, Basler & Hofmann, 1999).

Human factors are considered to some extent through the modelling of human actions. Human actions are identified in the accident sequences and the corresponding failure events are quantified using Human Error Probabilities (HEP) found in the literature for similar actions. The risk models included in the *manuals* and *case studies* contain example human actions as well as reference HEPs. Safety culture and organisational factors are among the human factors not explicitly addressed in the risk assessment process.

Table 2. **Main accident scenarios and functional events for LPG. For ammonia and chlorine, functional events coincide with main scenarios (SAEFL, 1996b & 1999, Basler & Hofmann, 1999)**

LPG		**Ammonia and Chlorine**
Main scenarios	Release categories (functional events)	Main scenarios
BLEVE	Large (catastrophic) leakage	Large (catastrophic) release
Flash fire	Large (catastrophic) leakage; continuous leakage	Large continuous release
		Small continuous release
Vapor cloud explosion	(none identified)	
Fire torch	continuous leakage	
Flying debris	(consequence of BLEVE scenario)	

Consequence assessment

The methods and models used for consequence assessment depend on the physical processes involved and on the event sequence scenarios considered. However in general, the following items are assessed for each scenario:

1. Quantity of hazardous substance(s) involved.
2. (Time dependent) intensity or concentration over the area exposed, taking into account the effect of terrain features and structures.
3. Exposure (i.e. number of people exposed, exposure time).
4. Possible consequence mitigation measures.

Below, the approach to consequence assessment in each of the three examples (LPG, chlorine and ammonia) is briefly outlined for one representative scenario:

LPG, BLEVE scenario: In a first step, the amount of LPG participating in the BLEVE is determined. From this, the fireball radius (R) can be calculated. Next, mortality rates are derived for people within the fireball radius R and within a three-fold fireball radius (3R). Different mortality rates are applied for people outside (directly exposed to the fireball) and for people inside buildings. Evacuation is usually not considered feasible in the scenario due to the absence of a useful warning time.

Chlorine, large catastrophic release (tank rupture): The propagation of the chlorine gas from the ruptured tank is calculated with the help of a computer model. The time-dependent distribution of the chlorine concentration (Figures 3a and 3b) is obtained including such factors as the surface roughness of the ground and the speed and direction of the prevailing wind at the time of the accident.

Figure 3a. **Chlorine distribution for a 60 kg leakage from a storage tank. Lines of equal concentration (1 000 ppm) for different values of surface roughness**

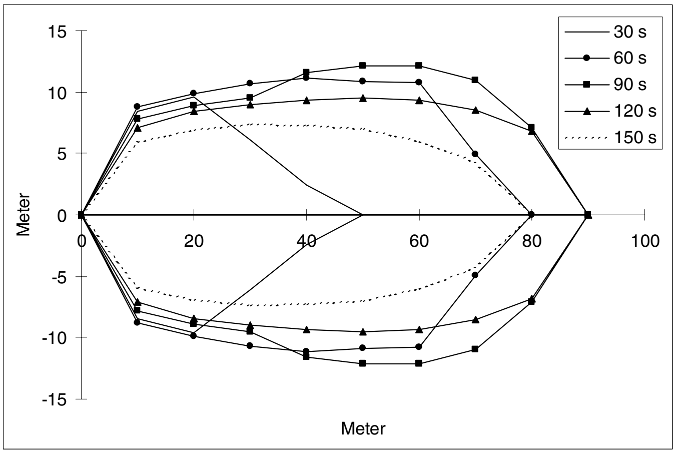
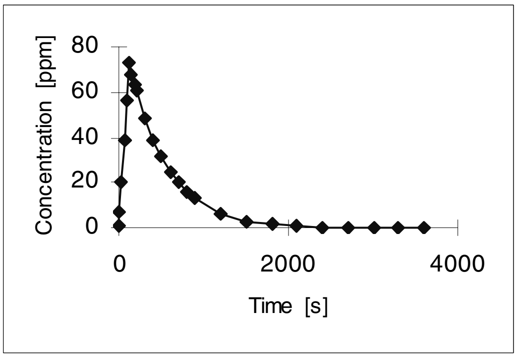


Figure 3b. **Time-dependent chlorine concentration in a building as the cloud passes by**



A dose-consequence relationship (probit function) is used to determine mortality as a function of the chlorine concentration and exposure time. For nearby buildings, separate chlorine concentrations are calculated assuming a constant air substitution rate. Evacuation is credited in the assessment of exposure times in scenarios where the warning time is sufficient to allow people to react and escape from the dangerous zone.

Ammonia, large (catastrophic) release: Similarly to the chlorine scenario described above, the time-dependent concentration of ammonia is calculated using a propagation program. A minimum required concentration for lethal exposure is used to delimit the perimeter within which exposure must be considered. Due to the speed with which the scenario develops, no credit is taken for evacuation.

Consequence mitigation measures can be (and should be, if adequate) included. They include the intervention of the fire brigade and evacuation of the population at risk. Credit can be taken for the fire brigade if it can be shown that there is a sufficient warning time for it to deploy. The success of evacuation generally depends on the warning time and on the population density in the exposed area as well as in the emergency evacuation routes (see also the examples of consequence assessment in section 5.1).

Risk estimation and risk comparison

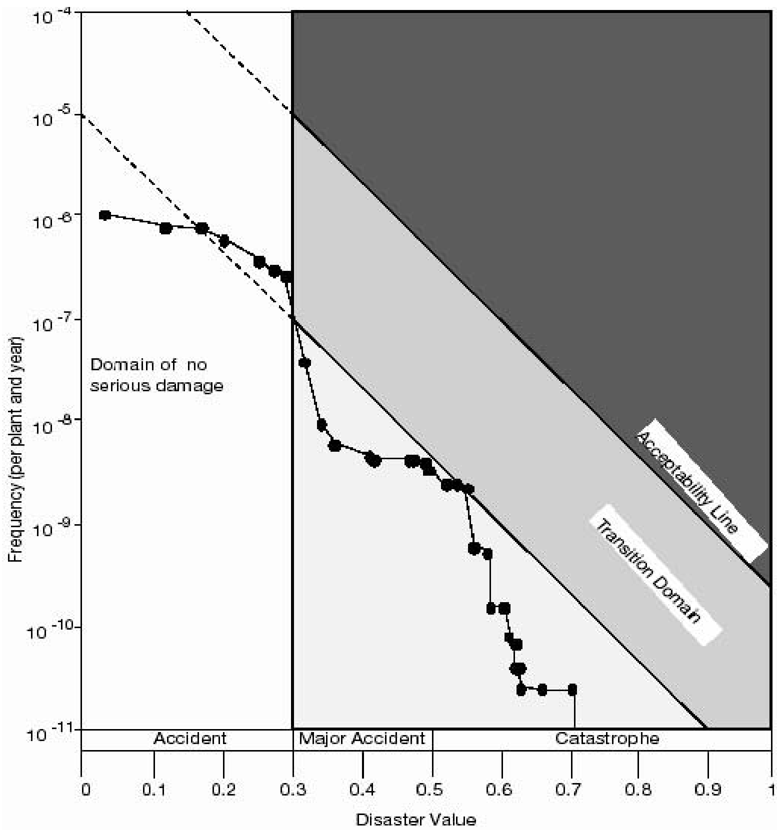
The likelihood of effects is expressed quantitatively in terms of the frequencies of the accident scenarios.

The diagram in Figure 4 is divided into four domains:

- no serious damage;
- acceptable;
- transition;
- unacceptable.

The slope of the boundary lines separating the three domains "acceptable", "transition" and "unacceptable" is quadratic. This is to account for the risk aversion commonly associated to accidents with large consequences. In risk estimation and risk comparison, the yearly frequencies of the relevant scenarios are plotted against the disaster values in a cumulative frequency distribution (Figure 4). From the cumulative frequency distribution, the acceptability or non-acceptability of the risk can be readily determined. Note that the slope of the boundary lines separating the three domains "acceptable", "transition" and "unacceptable" is quadratic. This is to account for the risk aversion commonly associated to accidents with large consequences.

Figure 4. **Societal risk criteria for major accidents (SAEFL, 1996c). Cumulative frequency diagram showing the number of fatalities (n_1) for the LPG storage example. The dots represent individual accident sequences.**



The enforcement authority evaluates the risk as follows (Figure 4):

1. If the cumulative frequency curve enters the unacceptable domain the owner of the facility is asked to reduce the risk, else the authority is empowered to take actions including operational restrictions or shutdown.
2. If the cumulative risk curve enters the transition domain, the enforcement authority will measure the interests of the facility owner against the needs of the public and the environment for protection from accidents. Depending on the outcome of these considerations, the risk has to be reduced to a level defined by the authority.
3. If the cumulative risk curve lies in the acceptable domain all through, the risk assessment procedure is complete. However, the owner must still take all appropriate measures to reduce risk (see below).

To obtain more insights on dominant risk contributors, separate curves can be plotted in the cumulative frequency diagrams grouping scenarios, which take their origin in the same initiator (Figure 5). A risk outlier can be defined as representing a substantial fraction of the total risk, where "substantial" is not further defined. A vulnerability is a risk outlier whose cause can be attributed to a system, type of component or operational practice of the installation under scrutiny. A vulnerability would further exist if a significant amount of risk were due to one particular type of accident (Figure 6).

Figure 5. **Cumulative frequency distribution showing the contribution of the different scenarios to the number of fatalities (n1) for the LPG storage example**

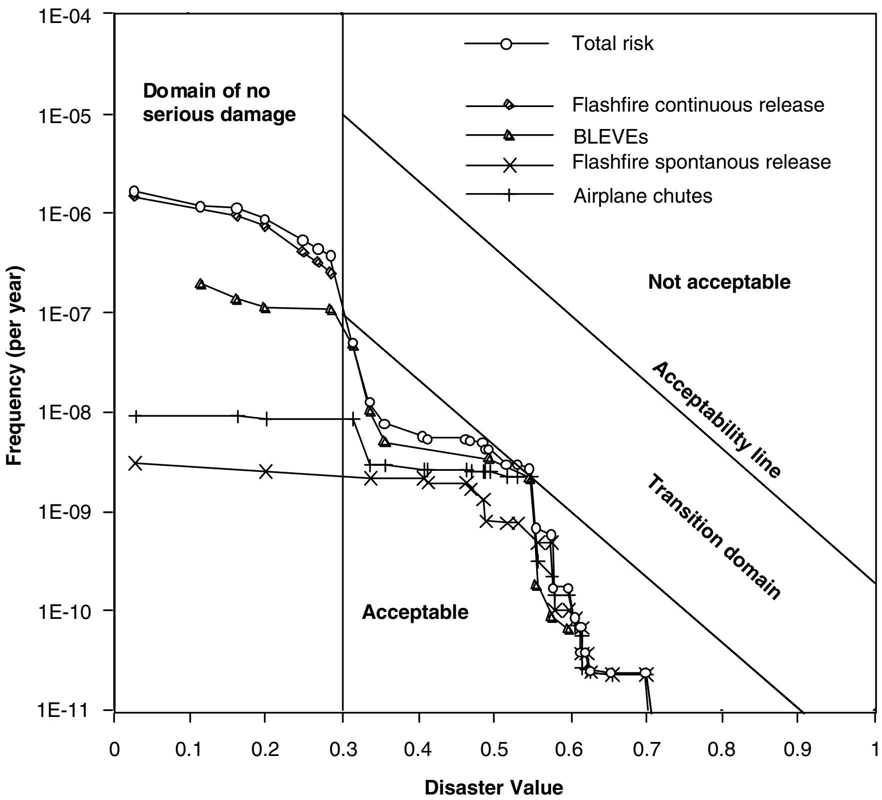
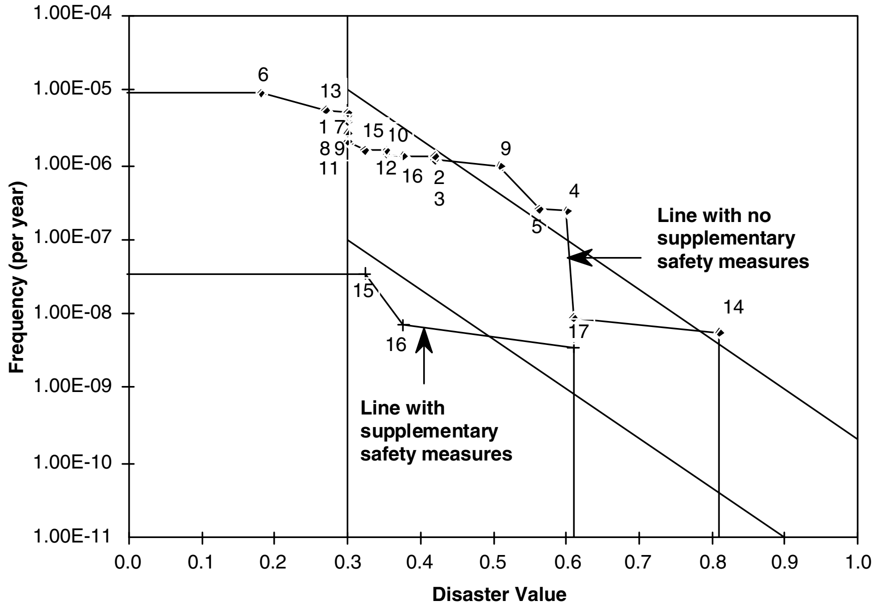


Figure 6. **Cumulative frequency distribution showing the number of fatalities (n1) for the example of the ammonia refrigeration plant in a public ice skating rink. The upper curve shows the risk before, the lower curve the risk after implementation of supplementary safety measures. The numbers correspond to individual accident scenarios**



Risk control in licensing and supervision of nuclear installations

Since the mid-eighties and the requirement for full-scope probabilistic risk studies (PSA) for nuclear power plant, control of risk from nuclear installations has played an increasingly important role in regulation in Switzerland. In 2005, a new legal framework will be introduced with the coming into force of the Nuclear Energy Act and its implementation rules, the Nuclear Energy Ordinance. The Energy Ordinance contains quantitative targets for the risk from nuclear installations. Furthermore, the Safety Guides issued by the Swiss Nuclear Safety Inspectorate HSK, currently under revision, will include guidelines for regulatory decision making which address both the risk and the uncertainties contained in the quantitative estimation of risk.

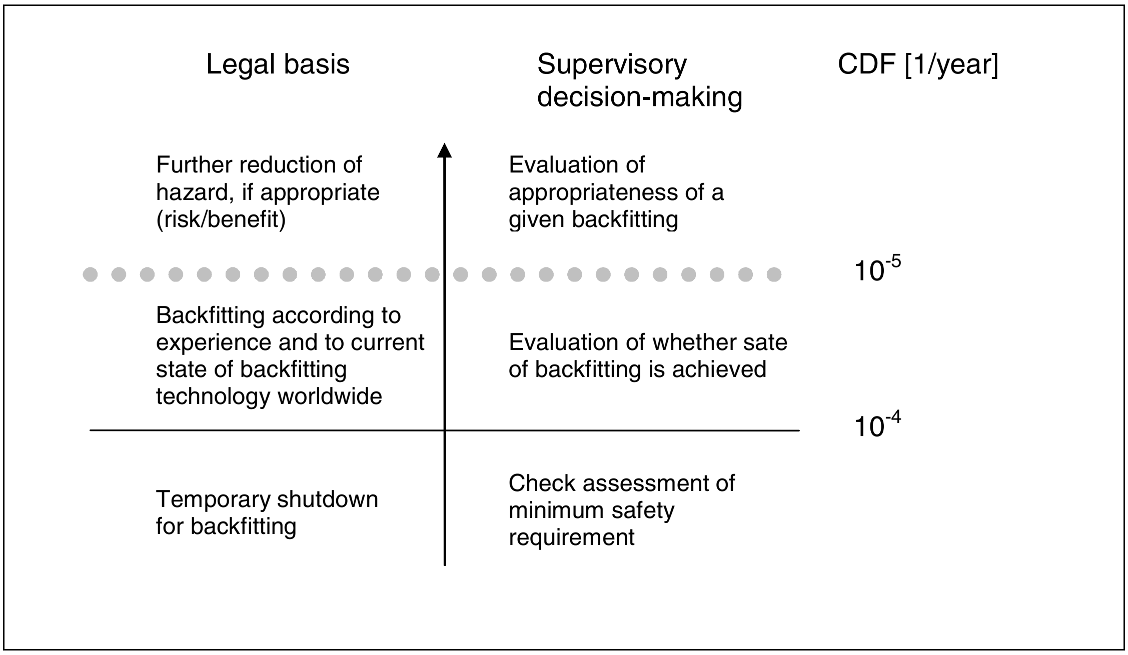
Legal basis

The Nuclear Energy Act requires the license holder to take the nuclear installation temporarily out of service and backfit it when certain criteria are met (article 22/3 of the Nuclear Energy Act). In response to this general rule, the Nuclear Energy Ordinance limits the total core damage frequency (CDF) for nuclear power plants. For new nuclear power plants commissioned after the coming into force of the Nuclear Energy Act, the CDF must be smaller than 10^{-5} per year and plant. For operating nuclear power plants, the CDF must be smaller than 10^{-4} per year and plant or else the plant must be temporarily shut down and backfitted. In fact, the target values recommended by the International Atomic Energy Agency (IAEA, 1992) are turned into firm shutdown rules by the Swiss regulations. Independently from probabilistic requirements, the Nuclear Safety Act also requires that operating nuclear power plants be "…backfitted to the extent necessary according to experience and the current state of retrofitting technology (worldwide), and beyond, provided this contributes to a further reduction of hazard and is appropriate" (article 22/2/g of the Nuclear Energy Act).

Supervisory decision making for the backfitting of nuclear power plants

Figure 7 depicts the proposed probabilistic basis for the future supervisory decision making process concerned with backfitting existing nuclear power plants (i.e. commissioned before the Nuclear Energy Act comes into force)[1]. Starting from the bottom of the picture, the lower safety limit for operating plants required by article 22/3 was set at a CDF of 10^{-4} per year. This corresponds to the value recommended by IAEA for operating nuclear power plants. Figure 7 also sets a target value at a CDF of 10^{-5} per year to discriminate between those backfits necessary to maintain safety with experience and the current state of retrofitting technology and those which further reduce hazard, if appropriate (article 22/2/g of the Nuclear Energy Act). For a well-balanced supervisory decision basis, these probabilistic criteria will have to be supplemented by criteria from design-basis and from operational experience.

Figure 7. **Core damage frequency (CDF) per year and legal basis and supervisory decision making**



The somewhat fuzzier delimiter used for the “state of the art” line means that the value is a target (recommended) value whereas the “minimum safe operations” line is considered a “hard” threshold. Note also that neither delimiter is frozen for all times: expected progress in safety technology is likely to move both delimiters towards lower values of CDF representing higher safety levels.

1. Although legally possible, the commissioning of new nuclear units in Switzerland within the next decade is not believed to be politically feasible. Consequently, as far as nuclear power plants are concerned, the Nuclear Energy Act and its ordinances will apply to existing units only.

Supervisory decision making for additional measures against severe accidents

Note that the decision-making framework proposed in Figure 7 is based on point-estimate (mean) values for the CDF. Figures 8a and 8b depict a somewhat more elaborate decision-making process where the uncertainty on the estimates is explicitly taken into account (Schmocker, 1997). The decision diagram in Figure 8b illustrates the steps of the decision-making procedure: if the 95%-fractile curve for the candidate nuclear power plant is smaller than the limiting curve for the mean ("limit mean"), then no further measures against severe accidents need to be considered. This would be the situation where the likelihood of core damage being lower than 10^{-5} per year could be demonstrated with 95% confidence (or conversely, that there is only a 5% chance that core damage is greater or equal to 10^{-5} per year). Next, the mean and 95%-fractile curves of the candidate nuclear power plant are checked against their respective limiting curves ("limit 95%" and "limit mean" respectively). If either of these criteria is violated, potential backfits against severe accidents need to be implemented regardless of costs involved ("Yes" path). If both criteria are met, potential improvements or backfits need to be implemented only if they are cost-effective ("No" path).

Figure 8a

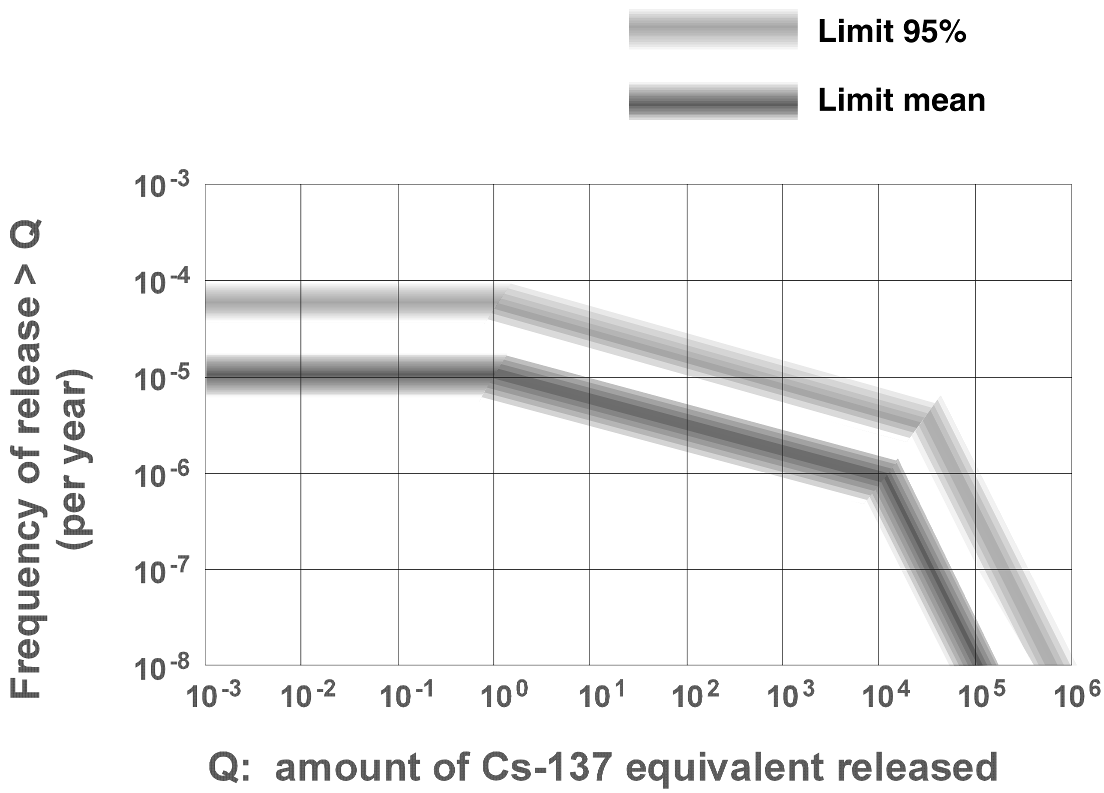
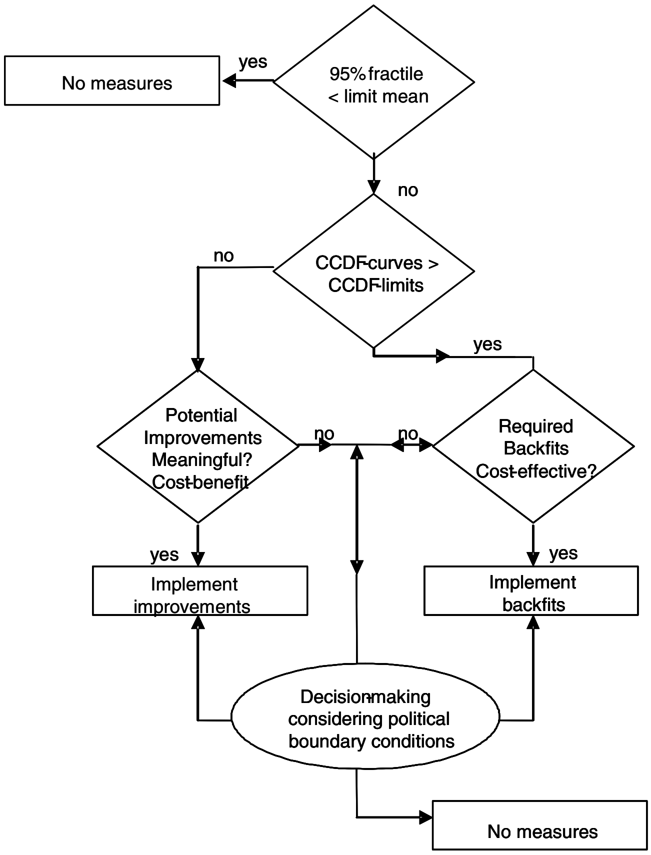


Figure 8b



This framework has been used by HSK to evaluate the appropriateness of additional measures to mitigate consequences of severe accidents in Swiss nuclear power plants. The frequency of release of radioactive aerosols (measured in terms of the amount of Caesium equivalent released) was chosen to evaluate the impact of severe accident measures. In contrast to the decision diagram depicted in Figure 7, which relies on a single point-estimate value, two percentiles (the mean value and the 95-percentile) from the release frequency distribution are independently controlled, effectively and explicitly involving the uncertainty of the estimate in the decision-making process. Note that uncertainty represented here as the difference between the mean and the 95-percentile of the distribution represents the sum total of epistemic and aleatory uncertainties which are quantified in the probabilistic model used to estimate release frequencies.

Decision making in the protection against major accidents vs. decision making in the control of nuclear risk

It is interesting to point out the differences in the two decision-making approaches described above. Although both of them are risk based, significant differences exist in system characteristics, in the approach and in the underlying methodology to quantify risk and uncertainty (Table 3).

Table 3. **Differences between two approaches**

	Chemical hazards (OMA)	NPP risk (Nuclear Safety Act)
System characteristics	Low to medium hazard potential. Hazard potential can be reduced.	Large hazard potential. Hazard potential difficult to reduce.
Decision-making approach	Hazard control through risk reduction.	Risk control through safety improvements.
Risk analysis methodology	Probabilistic, point estimate estimation.	Probabilistic, distributed input- and output parameters.
Treatment of uncertainty	Implicit, through reduction of risk.	Explicit. Risk criteria take into account uncertainty.
Backfitting rule	State of the art technology determines appropriate measures to reduce risk. Probabilistic target to determine supplementary safety measures to be implemented.	Probabilistic target for minimum safe operations. State of the art of backfitting technology must be implemented regardless of probabilistic target.

System characteristics

The OMA applies to installations with small to medium hazard potentials. Often, technological alternatives exist that allow more hazardous installations to be replaced by less hazardous ones (reduction in the amount of hazardous substances involved; changeover to a less risky technology altogether). The same is difficult to achieve for today's nuclear power plants: their radioactive inventory (hazard potential) is intimately linked to the power they produce. A reduction in hazard potential by a nuclear alternative would require a substantial technological step.

Decision-making approach

The decision-making approaches chosen are commensurate to system characteristics. Where risk reduction can be achieved by hazard control, the uncertainties on the remaining risks are minimised too. Where hazard control is not feasible, risk control is the (necessary) alternative.

Risk analysis methodology and treatment of uncertainties

There are only minor differences in the analysis and quantification of risks between the two approaches. Working with distributed parameters is a prerequisite to the explicit use of uncertainty in the decision-making process. One could argue that the treatment of uncertainties is implicit in the case of the OMA decision-making scheme: reducing risk to a residual level also reduces the uncertainties associated with those risks. In fact, this is the approach chosen by deterministic safety assessment, where safety substantial safety margins are used in design to rule out certain undesirable outcomes.

Backfitting rule

Backfitting is usually what drives the regulatory costs for existing installations. Consequently, backfitting rules are often important elements of regulation that reveal the true face of a decision-making approach. The most striking feature of both approaches is that they do not solely rely on risk criteria. Regardless of whether the risk criteria are met, the state of the art in safety technology must be implemented by the owner/the license holder.

Conclusions

- In Switzerland the Ordinance on Protection against Major Accidents (OMA, 1991) has been in force since 1 April 1991.

- Accompanying handbooks and guidelines published by the Swiss Agency for the Environment, Forests, and Landscape (SAEFL) which include an example of a summary report and a risk study as well as risk evaluation criteria have enhanced substantially the enforcement delegated to the Cantons.

- Hazard potentials have been reduced by many establishments with dangerous substances, products or special wastes below the quantity thresholds to avoid falling under the OMA.

- Safety measures in the great majority of establishments are now more thoroughly checked and updated if necessary.

- The OMA has initiated education and development of knowledge with regard to risk and safety. In particular, the Federal Institute of Technology at Lausanne and Zurich and at the University of St. Gall started postgraduate education in 1994 and many companies are keen to improve expertise.

- Information of the public is one of the main goals. However, the intention of the OMA is to disclose just the summary of the risk study on request. This rather restrictive information policy results from public indifference on the one hand and new regulations on privacy on the other.

- For many years, risk criteria have been a valuable tool for the targeted continuous improvement of the safety of nuclear power plants. In the future, risk-based decision making will receive a legal basis when the Nuclear Energy Act and the Nuclear Energy Ordinance become effective in the year 2005.

- In risk-control for nuclear power plants, decision making is moving from the use of point-estimate values towards the explicit consideration of epistemic and aleatory uncertainties.

Some thoughts from the perspective of safety assessment for nuclear waste repositories

The assessment of the hazards of nuclear waste repositories is specified in the Swiss regulatory guide HSK-R-21. The more likely scenarios for the release of radioactive substances are assessed deterministically using conservative assumptions to control uncertainties. The less likely scenarios have to meet a risk target, where the risk measure is the product of probability and consequences. A safety report is required that contains elements in analogy to the summary report for installations that fall under the OMA. But unlike in the case of the OMA, the elements are evaluated quantitatively. An important difference to both OMA and NPP safety is that nuclear waste repositories cannot rely on mitigation to prevent inadmissible releases, since such releases would take place in the far future. The repository has to be designed based on passive safety. While dose or dose risk is the primary measure, additional indicators such as the release of radionuclides across defined system boundaries or concentrations of radionuclides in defined system parts are used to characterise the safety of nuclear waste repositories. This could be compared to the choice of damage indicators of the OMA. As for scenario analysis, the main observation is that in the repository safety analyses, the description of the baseline case itself (the reference or "null" scenario) is very labour-intensive, since this first step is by no means trivial and requires challenging predictions into the future. In safety analyses performed so far, the possible risk target has not been used, but probabilistic calculations have been used to assess the effects of multiple uncertain parameters in particular scenarios. The results of these calculations were shown as cumulative damage frequency curves similar to the one in Figure 8a.

References

Basler & Hofmann (1992), *Manual for LPG Storage Vessels regarding the Summary Report and the Risk Study in Relation to Protection Against Major Accidents* (in French and German). Basler & Hofmann Consulting Engineers, Forchstrasse 395, CH-8029 Zürich, Switzerland.

Basler & Hofmann (1999), *Case Study of a Risk Study for a Chlorine-Based Cleansing Plant in a Public Swimming Pool* (in German). Basler & Hofmann Consulting Engineers, Forchstrasse 395, CH-8029 Zürich, Switzerland.

Carbura (1999), *Manual for the Safety of Large Mineral Oil Storage Facilities.* CARBURA and Swiss Agency for the Environment, Forests and Landscape (SAEFL), (revision 11), Zurich, Switzerland.

EC Directive 90/219 (1990), on the Contained Use of Genetically Modified Micro-organisms.

EC Directive 96/82 (1996), Seveso II Directive on the Control of Major Accidents Hazards Involving Dangerous Substances.

IAEA (1992), IAEA Safety Series No. 106, "The Role of Probabilistic Safety Assessment and Probabilistic Safety Criteria in Nuclear Power Plant Safety", 1998.

LPE (1983), Law Relating to the Protection of the Environment. Bundesgesetz vom 7. Oktober 1983 über den Umweltschutz (USG), SR 814.01, Berne, Switzerland.

OMA (1991), *Swiss Ordinance on Protection Against Major Accidents* (Ordinance on Major Accidents, OMA), SR 814.012, (in English, French or German) February 27, 1991 (Updated July 1994), Berne, Switzerland.

SAEFL (1991), Handbook I for the Ordinance on Major Accidents, OMA, Guidelines for Establishments with Substances, Products or Special Wastes (in French or German), Swiss Agency for the Environment, Forests and Landscape, SAEFL, Berne, Switzerland.

SAEFL (1996a), *Umweltschutz*, monthly publication of the Swiss Agency for the Environment, Landscape and Forests, SAEFL, Nr. 3/96, March 1996 (in German), Berne, Switzerland.

SAEFL (1996b), *Case Study of a Risk Study for a LPG Storage Vessel, Ordinance on Major Accidents* (in French or German), Swiss Agency for the Environment, Forests and Landscape (SAEFL), Berne, Switzerland.

SAEFL (1996c), Evaluation Criteria for the Ordinance on Major Accidents, OMA, Evaluation of the Extent of Damage, Evaluation of the Acceptability of Risk, Guidelines for Establishments with Substances, Products or Special Wastes (in French or German), Swiss Agency for the Environment, Forests and Landscape (SAEFL), Berne, Switzerland.

SAEFL (1999), *Case Study of a Risk Study for an Ammonia-Based Cooling Process in a Public Ice Rink* (in French or German, draft edition). Basler & Hofmann Consulting Engineers, Forchstrasse 395, CH-8029 Zürich, Switzerland.

Schmocker, U. (1997), *Technische Massnahmen zur Begrenzung der Folgen schwerer Unfälle*. SVA-Vertiefungskurs "Notfallmanagement innerhalb und ausserhalb des KKW", Winterthur, 15.-17. Oktober, 1997.SNGC (1997), *Manual for the Safety of High Pressure Natural Gas Installations.* Swiss Natural Gas Company (revised edition), Zürich, Switzerland.

DEVELOPMENT OF SAFETY CRITERIA IN GERMANY: AIM, PROCESS AND EXPERIENCES

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Introduction

Presently, a new plan for the management of radioactive waste in Germany is under development. Amongst the important cornerstones of this plan are the development and implementation of a new siting procedure, known under the acronym AkEnd ("Arbeitskreis Auswahlverfahren Endlagerstandorte" = Committee on a Selection Procedure for Repository Sites, AKEnd 2002a, b) and a revision of the Safety Criteria for the disposal of radioactive waste in a mine which were issued in 1983 (BMI, 1983). The revision is being carried out in order to account for the important developments in Germany and abroad in the fields of final radioactive waste disposal and repository performance assessment which have taken place over the last decades, to comply with the international state of the art in science and technology and to be consistent with the international development.

On behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), GRS Köln drafted a proposal for the revision. The drafting process was supported by a body composed of experts from several German organisations and from abroad. The proposal was reviewed by the BMU's advisory committees RSK (Reactor Safety Commission) and SSK (Commission on Radiological Protection). An updated draft which takes into account the committees' comments was submitted to the BMU and is currently considered in order to establish and issue updated Safety Criteria. In parallel, a supporting guideline with requirements and recommendations for the post-closure Safety Case is being developed by GRS Köln, again with the support of experts from several German organisations and from abroad. This development has had and will have further implications for the revision of the Safety Criteria.

The proposals for revised criteria and for the guideline are based on national laws and regulations, especially the Atomic Energy Act (ATG, 2002) and the Radiation Protection Ordinance (StrlSchV 2001) as well as on recent international regulations and recommendations such as:

- IAEA Regulations e.g. the Fundamental principles for the safe handling of radioactive wastes (IAEA, 1995).
- The act on the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (BGB, 1998).
- Norms of the European Communities (e.g. EURATOM, 1996).
- ICRP regulations (e.g. ICRP, 1998).
- OECD recommendations.

Amongst the latter, the most recent NEA developments within the Integration Group for the Safety Case (IGSC) concerning the post-closure Safety Case for radioactive waste repositories, namely the drafting of the "Safety Case Brochure", were of utmost importance.

The criteria are exclusively related to radiation protection objectives and requirements specifying the damage precaution required by the Atomic Energy Act (ATG, 2002). The draft criteria require a multi-barrier system but place, in accordance with the AkEnd requirements, emphasis on the geologic barrier. They contain:

- Safety principles.
- Radiation protection objectives for the operational and the post-operational phases.
- Site requirements.
- Planning principles for the safety concept.
- Design and erection requirements.
- Criteria for the operational phase.
- Criteria for the post-operational phase (Long-term safety demonstration).

The elements required for the long-term safety demonstration are:

- Site characterisation.
- Geological and geotechnical long-term prognosis.
- Realisation of the safety concept.
- Fulfilment of the planning principles.
- Proof of criticality safety.
- Integrated safety assessment based on multiple lines of arguments using various performance and safety indicators.
- Demonstration of compliance with the safety goals.

This paper focuses on the choice of calculation end points for the required safety assessment and on how the uncertainties inevitably linked to such assessments have to be addressed.

Choice of calculation endpoints

The central radiological protection objective for the post-operational phase is to limit the risk of an individual sustaining serious health damage from exposure to radiation. The validity of this objective is unlimited in time. The applicability of the demonstration methods and the reliability of their results are, however, temporally limited since the time frames for safety assessments rely on the ability of geological and geotechnical prognosis concerning the future evolution of the repository system. It is stated in the draft criteria that beyond the time span of reasonable geological prognosis (ca.10^6 years) no credibility can be attached to integrated safety assessments and that, therefore, no assessments exceeding this timeframe should be undertaken.

The question of which calculation endpoint(s) for safety assessments would serve best the radiological protection objective "to limit the risk of an individual sustaining serious health damage from exposure to radiation" was exhaustively discussed by the experts involved in the criteria and guidelines developments. The most general interpretation of the word "risk" given by the IAEA Safety Glossary (IAEA, 2000) is:

"1. A multiattribute quantity expressing hazard, danger or chance of harmful or injurious consequences associated with actual or potential exposures. It relates to quantities such as the probability that specific deleterious consequences may arise and the magnitude and character of such consequences."

This definition is accompanied by the explanation

"In mathematical terms, this can be expressed generally as a set of triplets, R = {<S_i|p_i|X_i>}, where S_i is an identification or description of a scenario i, p_i is the probability of that scenario and X_i is a measure of the consequence of the scenario. The concept of risk is sometimes also considered to include uncertainty in the probabilities p_i of the scenarios."

The glossary also offers a definition which is in accordance with the widely used notion of "risk":

"2. The mathematical mean (expectation value) of an appropriate measure of a specified (usually unwelcome) consequence:

$$R = \sum_i p_i \cdot c_i$$

where p_i is the probability of occurrence of scenario or event sequence i and C_i is a measure of the consequence of that scenario or event sequence."

Amongst the explanations supplementing this definition are:

"The summing of risks associated with scenarios or event sequences with widely differing values of C_i is controversial. In such cases the use of the term "expectation value", although mathematically correct, is misleading and should be avoided if possible.

Methods for treating uncertainty in the values of p_i and C_i and particularly whether such uncertainty is represented as an element of risk itself or as uncertainty in estimates of risk, vary."

In addition, the glossary gives a third notion by saying:

"3. The probability of a specified health effect occurring in a person or group as a result of exposure to radiation."

This is accompanied by the explanations:

"The health effect(s) in question must be stated – e.g. risk of fatal cancer, risk of serious hereditary effects, or overall radiation detriment – as there is no generally accepted "default".

Commonly expressed as the product of the probability that exposure will occur and the probability that the exposure, assuming that it occurs, will cause the specified health effect. The latter probability is sometimes termed the conditional risk."

Assuming that the annual "risk of an individual sustaining serious health damage from exposure to radiation" is proportional to the dose rate of this exposure, the question remained, to what extent

- this dose rate and the likelihood to receive it; and
- the dose rates caused by different scenarios.

should be either presented separately or aggregated in calculation endpoints. The determination of a "total risk" like the expectation value given in the second IAEA definition can be seen as the highest degree of aggregation of these entities into one single number. However, the choice of the degree of aggregation should be determined by:

- the underlying philosophy;
- the practicalities concerning the assessment calculations to be carried out; and
- the practicalities of presenting results and communicating them.

Within the criteria development, it was seen as desirable to prescribe a dose constraint for likely scenarios (including the so-called expected evolution). However, for other (residual) scenarios the possibility of weighing low likelihoods against potentially high consequences was seen as sensible.

There were diverging views about how the weights (likelihoods) have to be determined for such scenarios which are governed by a (short-term) event (e.g. an earthquake). If one takes the perspective of a potentially exposed person and assumes that the annual risk that this person will sustain serious health damage is proportional to the annual dose this person is exposed to, this annual dose would have to be weighed against the likelihood that exactly this person will receive this dose. Such an approach would lead to risk as given in the second and third notions of the IAEA glossary as calculation endpoint for such a scenario.

However, given the extremely long timeframes of concern in long-term safety assessments, one could also (taking the position that an implementer wants to avoid any harm no matter when it might occur) arrive at the conclusion that the **total probability** that a scenario (i.e. its initiating event) occurs **at an arbitrary time** in the assessment timeframe should be the appropriate weight. Provided that the timeframe in which a scenario causes a significant dose rate is orders of magnitude lower than the assessment timeframe, this would, for short-term initiating events, lead to weights orders of magnitude higher than in the first approach. In the jargon of the experts involved in the criteria development, the approaches were called the "culprit's perspective" and the "victim's perspective", respectively.

Several proposals were discussed for the assessment endpoints. Amongst them were constraints for the residual risk for less likely scenarios in the form of a weighted sum of consequences, the weights being likelihoods of occurrence derived either from the "victim's" or the "culprit's perspectives". Finally, the following approach was agreed on:

- It shall be distinguished between "likely scenarios", "less likely scenarios" and "scenarios not to be considered in assessment calculations". In addition, "scenarios assuming direct human intrusion into the repository" shall form a separate group.

- For the likely scenarios, a dose constraint of 0.1 mSv/a was defined, while a constraint of 1 mSv/a shall apply to the less likely scenarios. A stylised biosphere model to determine individual doses from radionuclide concentrations/fluxes will be specified in a guideline based on present-day habits.

- Parameter uncertainties and uncertainties amenable to parametrisation shall be accounted for within probabilistic calculations. A dose constraint is regarded to be met if the uncertainty analysis gives 90% statistical confidence that the 90^{th} percentile of the underlying "true" distribution lies below the constraint.

- A limited number of scenarios assuming direct human intrusion to be studied will be defined in a guideline based on present-day practises in Germany. The objective of studying these scenarios is rather to justify siting and design decisions than to demonstrate compliance with a numerical criterion.

- The guideline which is presently being developed will provide guidance on how to classify scenarios based on their likelihood of occurrence. This guidance will be orientated on total likelihoods (that is, likelihoods that a scenario will occur at an arbitrary point of the assessment timeframe). The guidance will distinguish between scenarios caused by (unknown) features and by (natural or anthropogenic) processes and events. A "virtual threshold" of 10% likelihood of occurrence will be used as a background for distinguishing between likely and less likely scenarios, but no request to calculate such likelihoods will be formulated. For naturally caused processes and events, the guidance will be based on an extrapolation of the geological past of the site and comparable sites.

This approach and especially the decision to go without a risk calculation endpoint were based on a number of considerations, the most important ones being the following:

- Serious doubts were expressed concerning the possibility to quantify likelihoods of occurrence for the majority of the scenarios possibly to be considered.
- Even if it were possible to quantify (e.g. annual) likelihoods of occurrence for short term initiating events, it would be complicated to account for these likelihoods appropriately in a weighing scheme for potential consequences from different scenarios and it would be hard to communicate results of such assessments, especially since there would also be other uncertainties (e.g. concerning duration of exposure) to be considered in the calculation and presentation. The only reasonable way to do this would be a fully probabilistic assessment and it was not seen as desirable to prescribe such an assessment approach. However, the implementer would in the chosen approach still have the freedom to regard the time of occurrence of a scenario as an uncertain parameter to be addressed within a probabilistic assessment, provided he were able to choose the corresponding probability density function in a convincing way.
- A weighing using total probabilities ("culprit's perspective") would, although in principle desirable, produce a calculation endpoint which would not be comparable with the usual notion of "risk".
- Even though dose rates calculated in assessments are seen as indicators rather than as predictions, the BMU's advisory committees in their recommendations expressed, from a radiation protection point of view, serious concerns with regard to approaches which would allow "compensating" severe consequences by weighing them with low likelihoods of occurrence. Potential exposures of more than 1 mSv/a were seen as problematic regardless of the likelihood of occurrence.

Treatment of uncertainties

It will be distinguished between scenario, model and parameter uncertainties, being aware that such a categorisation is always somewhat arbitrary, subjective and dependent on the chosen modelling and assessment approaches. The possibility to parametrise times of occurrence for scenario initiating events (cf. above) might serve as only one amongst numerous examples for this. No distinction will be made between so-called subjective and so-called stochastic uncertainties.

According to recent developments, assessment calculations are seen as one of multiple lines of evidence to be provided in a Safety Case. The bulleted list at the end of the introduction of this paper gives other areas which are addressed in the Safety Criteria.

Scenario uncertainties

Uncertainties concerning potential future evolutions of the repository system are addressed by requiring a well-structured procedure for the development of scenarios in order to ensure that a comprehensive set of reasonable scenarios will be considered. The procedure should make use of national and international FEP databases and ensure the traceability of every decision made during the development process. The extent to which the character of such a procedure will be prescribed still needs to be decided.

The scenarios will be classified and assessed as described above. Whether or not a scenario is described "correctly" is seen as being subject to model uncertainty (cf. below).

The choice of scenarios with highly speculative character, namely of those assuming direct human intrusion, is guided as described above. Whether or not other rather speculative scenarios are considered (e.g. so-called "what if"-scenarios which might allow demonstrating robustness of certain repository components), depends on choices and decisions to be made by the implementer (possibly in dialogue with the regulator).

Model uncertainties

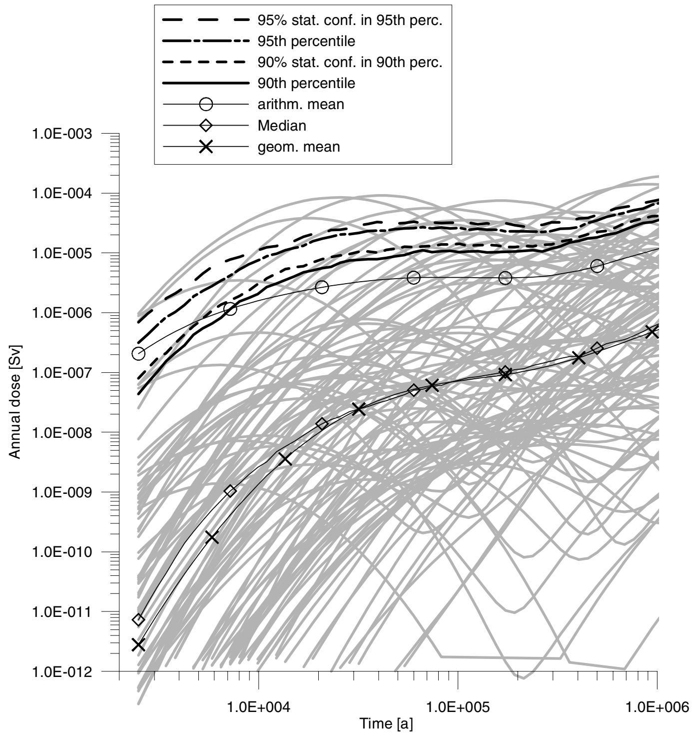
The conceptual, mathematical and numerical models (including codes) to be used in the assessments shall be developed according to established quality assurance procedures. Verification, validation and confidence building shall be carried out according to the state of the art in science and technology. If there are doubts concerning modelling assumptions or with regard to the presence and/or nature of processes, alternative assumptions shall be explored. If possible, conservative assumptions should be used and/or the robustness of the system against such uncertainties should be demonstrated.

Where, as in the case of biosphere modelling, there is room for highly speculative assumptions, the choice of such assumptions will be guided by regulations.

Parameter uncertainties

For uncertain parameters or assumptions amenable to quantification, either conservative choices are to be made or reasonable probability density distributions are to be derived. In either case, decisions have to be justified and to be documented in a traceable manner. For each likely or less likely scenario to be considered in assessment calculations, a probabilistic uncertainty analysis has to be carried out. As said above, a dose target for a scenario is considered to be met if, with 90% statistical confidence, the 90^{th} percentile of the "true" distribution underlying the uncertainty analyses lies below the constraint. This fulfilment of this requirement can be demonstrated independent of the shape of the underlying probability distribution (Guttman 1970). The requirement is, e.g., fulfilled if 913 out of 1 000 realisations lie below the constraint. The choice of the 90^{th} percentile and the 90% statistical confidence limit is still seen as preliminary. In contrast, a requirement that, e.g., the 95^{th} percentile lies with 95% statistical confidence below the constraint would be fulfilled if 962 realisations out of 1 000 would be below the constraint, while 90% confidence with regard to the 95^{th} percentile would require 960 out of 1 000 realisations lying below the constraint. The figure below gives an impression of how to compare these so-called "distribution-independent tolerance limits" with other well-known statistics.

Figure 1. **Dose rate results and statistics for a trial probabilistic assessment run (earthquake scenario). The statistics were calculated for 1 000 realisations; however, only the first 100 runs are displayed (grey lines).**



Concluding remarks

As stated in the introduction, the revision of Safety Criteria is not yet complete. Thus, the paper represents a preliminary status. This applies especially to the content of the supporting regulatory guidelines.

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References

Arbeitskreis Auswahlverfahren Endlagerstandorte – AkEnd (2002a) Site Selection Procedure for Repository Sites. Recommendations of the AkEnd – Committee on a Site Selection Procedure for Repository Sites. Final report, December 2002, http://www.akend.de/englisch/pdf/finalreport.pdf.

Arbeitskreis Auswahlverfahren Endlagerstandorte – AkEnd (2002b) Site Selection Procedure for Repository Sites. Recommendations of the AkEnd – Committee on a Site Selection Procedure for Repository Sites. AkEnd-brochure, December 2002, http://www.akend.de/englisch/pdf/broschuere_endg_eng.pdf.

ATG (2002), Act on the Peaceful Utilization of Atomic Energy and the Protection against its Hazards (Atomic Energy Act) of December 23, 1959 (Federal Law Gazette <BGBl.> I 1959, page 814), as Amended and Promulgated on July 15, 1985 (Federal Law Gazette <BGBl.> I 1985, page 1565), Last Amendment by the Act of April 22, 2002 (Federal Law Gazette, <BGBl.> I 2002, page 1351).

BGB (1998), Gesetz zu dem Gemeinsamen Übereinkommen vom 5. September 1997 über die Sicherheit der Behandlung abgebrannter Brennelemente und über die Sicherheit der Behandlung radioaktiver Abfälle (Act on the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management) BGBl Teil II, Nr. 31,S. 1752, 1998.

Bundesministerium des Innern (BMI 1983), Sicherheitskriterien für die Endlagerung radioaktiver Abfälle in einem Bergwerk (Safety Criteria for the Final Disposal of Radioactive Wastes in a Mine). GMBI. 1983, S. 220.

EURATOM (1996), Council Directive 96/29/EURATOM laying down Basic Safety Standards for the Protection of the Health of Workers and the General Public against the Dangers arising from Ionising radiation, Official Journal of the European Communities, L159, 29 June, 1996.

Guttman, I. (1970), Statistical Tolerance Regions: Classical and Bayesian. Griffin, London.

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

IAEA (2000), IAEA Safety Glossary. Terminology Used in Nuclear, Radiation, Radioactive Waste and Transport Safety. Version 1.0.

International Commission of Radiological Protection (ICRP 1998) Radiation Protection Recommendations as Applied to the Disposal of Longlived Solid Radioactive Waste. Publication 81. Annals of the ICRP, Vol. 28, No 4.

StrlSchV (2001), Verordnung über den Schutz vor Schäden durch ionisierenden Strahlen – Strahlenschutzverordnung StrlSchV (Radiation Protection Ordinance) (Federal Law Gazette <BGBl.> I 2001, page 1713).

CONSIDERATION OF UNLIKELY EVENTS AND UNCERTAINTIES IN THE FINNISH SAFETY REGULATIONS FOR SPENT FUEL DISPOSAL

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Introduction

Spent fuel disposal programme in Finland passed in 2001 the decision-in-principle process that is crucial to the selection of the disposal site and to obtaining the political acceptance for the disposal plan. The regulator (STUK) participated in the process by reviewing implementer's (Posiva) safety case. The review was based on the general safety regulation[1] issued by the Government in 1999 and STUK's guide[2] of 2001 for the long-term safety specifying the general safety regulation. These regulations address also unlikely natural and human scenarios and related uncertainties. The criteria adopted for the judgment of the radiological impact from such scenarios depend on the type of scenario and the time period of concern.

General safety regulations

The general safety regulations give a dose based radiation protection criteria for normal evolution scenarios, which take place during the so called environmentally predictable future. For normal evolution scenarios occurring beyond that time period, the radiation protection criteria are based on the release rates of disposed radionuclides into the biosphere. The regulations include also specific criteria for dealing with unlikely disruptive events affecting long-term safety and for dealing with uncertainties involved with the assessments. The radiation protection criteria included in the general safety regulations are given below (in italics) and discussed in the subsequent chapters.

"In an assessment period that is adequately predictable with respect to assessments of human exposure but that shall be extended to at least several thousands of years:

- *the annual effective dose to the most exposed members of the public shall remain below 0.1 mSv and*
- *the average annual effective doses to other members of the public shall remain insignificantly low.*

Beyond the assessment period referred to above, the average quantities of radioactive substances over long time periods, released from the disposed waste and migrated to the environment,

1. General regulations for the safety of spent fuel disposal (1999), Government Decision 478/1999 (1999).
2. Long-term safety of disposal of spent nuclear fuel, STUK Guide YVL 8.4 (2001).

shall remain below the nuclide specific constraints defined by the Radiation and Nuclear Safety Authority. These constraints shall be defined so that:

- *at their maximum, the radiation impacts arising from disposal can be comparable to those arising from natural radioactive substances; and*
- *on a large scale, the radiation impacts remain insignificantly low.*

The importance to long-term safety of unlikely disruptive events impairing long-term safety shall be assessed and, whenever practicable, the acceptability of the consequences and expectancies of radiation impacts caused by such events shall be evaluated in relation to the respective dose and release rate constraints.

Compliance with long-term radiation protection objectives as well as the suitability of the disposal concept and site shall be justified by means of a safety analysis that addresses both the expected evolutions and unlikely disruptive events impairing long-term safety. The safety analysis shall consist of a numerical analysis based on experimental studies and be complemented by qualitative expert judgement whenever quantitative analyses are not feasible or are too uncertain.

The data and models introduced in the safety analysis shall be based on the best available experimental data and expert judgement. The data and models shall be selected on the basis of conditions that may exist at the disposal site during the assessment period and, taking account of the available investigation methods, they shall be site-specific and mutually consistent. The computational methods shall be selected on the basis that the results of safety analysis, with high degree of certainty, overestimate the radiation exposure or radioactive release likely to occur. The uncertainties involved with safety analysis and their importance to safety shall be assessed separately."

Environmentally predictable future

The regulations define the so-called environmentally predictable future which is assumed to extend up to several thousands of years. During this period, the climate type is expected to remain similar to that nowadays in Northern Europe. However, considerable but predictable environmental changes will occur at the disposal site due to the ongoing land uplift: a sea bay will turn into a lake, then into wetland and the sediment might later on be used as farmland. The geosphere is expected to remain quite stable though slight, predictable changes will occur due to the land uplift and the heat generating waste.

In this timeframe, the engineered barriers are required to provide almost complete containment of the disposed waste in order to minimise the impacts from waste induced disturbances and to facilitate retrievability of waste. Consequently, people might be exposed to the disposed radioactive substances only as a result of early failures of engineered barriers, due to e.g. fabrication defects or rock movements.

Despite the environmental changes, conservative estimates of human exposure can be done for this time period and accordingly the safety criteria are based on dose constraints. In the STUK guide,[2] the radiation protection criteria are clarified as follows:

"The dose constraints apply to radiation exposure of members of the public as a consequence of expected evolution scenarios and which are reasonably predictable with regard to the changes in the environment. Humans are assumed to be exposed to radioactive substances released from the repository, transported to near-surface groundwater bodies and further to watercourses above ground. At least the following potential exposure pathways shall be considered:

- *use of contaminated water as household water;*
- *use contaminated water for irrigation of plants and for watering animals;*
- *use of contaminated watercourses and relictions.*

Changes in the environment to be considered in applying the dose constraints include at least those arising from land uplift. The climate type as well as the human habits, nutritional needs and metabolism can be assumed to be similar to the current ones.

The constraint for the most exposed individuals, effective dose of 0,1 mSv per year, applies to a self-sustaining family or small village community living in the vicinity of the disposal site, where the highest radiation exposure arises through the pathways discussed above. In the environs of the community, a small lake and shallow water well is assumed to exist.

In addition, assessment of safety shall address the average effective annual doses to larger groups of people, who are living at a regional lake or at a coastal site and are exposed to the radioactive substances transported into these watercourses. The acceptability of these doses depend on the number of exposed people, but they shall not be more than one hundredth – one tenth of the constraint for the most exposed individuals.

The unlikely disruptive events impairing long-term safety shall include at least:

- *boring a deep water well at the disposal site;*
- *core-drilling hitting a waste canister;*
- *a substantial rock movement occurring in the environs of the repository.*

The importance to safety of any such incidental event shall be assessed and whenever practicable, the resulting annual radiation dose or activity release shall be calculated and multiplied by the estimated probability of its occurrence. The expectation value shall be below the radiation dose or activity release constraints given above. If, however, the resulting individual dose might imply deterministic radiation impacts (dose above 0,5 Sv), the order of magnitude estimate for its annual probability of occurrence shall be 10^{-6} at the most."

The radiation protection criteria involve flexibility for the assessment of unlikely disruptive events. Whenever practicable, the assessment should be done in an aggregated way by calculating a radiation dose and the probability of its occurrence and by comparing the resulting expectation values with the respective dose constraints. But the regulations recognise that, due to inherent uncertainties, this is not always feasible and consequently allow also a more disaggregated and less quantitative assessment of consequences and probabilities of unlikely disruptive events.

The regulations specify three unlikely disruptive events that should at least be included in the list of scenarios to be analysed: a deep water well, core drilling and rock movement.

The water well scenario is quite natural because in Finland, tens of thousands of water wells bored at the depth of a couple of tens to hundreds of meters exist. Thus it is quite likely that such a well will exist at the disposal site at some time. The well might short-circuit the transport pathways of contaminated groundwaters and enhance radiation exposure of the critical group.

Considerable uncertainties relate to the analysis of the water well scenario. In order to calculate the arising radiation dose, the dilution factor should be known. Though illustrative analyses give a quite wide range for the dilution factor in case of crystalline rock, a reasonably conservative value can be adopted. The probability of the existence of a water well at the disposal site at a certain time, so that the people using the water are unaware of its radioactive contamination, is more speculative. Nevertheless, the deep water well scenario should be analysed quantitatively, taking into account the involved uncertainties, and the results should be discussed in relation to the radiation dose constraint.

Core drilling, hitting a waste canister, is a very speculative scenario. A reference scenario, preferably internationally adopted one, should be developed for the analysis of the radiological consequences of such events. Some estimates for probabilities, based on current frequencies of deep drilling, can be obtained, but their projection into far future is questionable. Because the probabilities are very low and the consequences can be even serious, the core drilling scenario should be assessed in a disaggregated manner.

The rock movement scenario involves an event where a seismic or aseismic phenomenon in the vicinity of the repository causes secondary rock displacements, one of which might intersect waste canisters. In Finland, such events are most likely in postglacial conditions, when the rock stresses induced during ice age are relieved and consequently, the intensities and frequencies of rock movements are by far higher than today. During the past few years, significant progress in the quantitative analysis of probabilities of such events has been achieved. Anyway, large uncertainties are involved with both consequences and probabilities of such scenarios and in the safety assessment, they should be dealt with in a disaggregated manner.

Era of extreme climate changes

Beyond about 10 000 years, great climatic changes, such as permafrost and glaciation, will emerge. The range of potential environmental conditions will be very wide and assessments of potential human exposures arising during this time period would involve huge uncertainties. A conservative safety case should be based on extreme bioscenarios and overly pessimistic assumptions.

The climatic changes affect significantly also the conditions in the geosphere, but their ranges are estimable. In this time period, substantial degradation of the engineered barriers cannot be ruled out, though they were planned to withstand the stresses due to the climate-induced disturbances in bedrock. As radionuclide release and transport in the repository and geosphere can be assessed with reasonable assurance and consequently, it is prudent to base the radiation protection criteria on constraints for release rates of long-lived radionuclides from geosphere to biosphere (so called geo-bio flux constraints).

In STUK's guide,[2] the general safety criteria addressing the era of extreme climate changes (see chapter 2) are specified as follows:

"The nuclide specific constraints for the activity releases to the environment are as follows:

- *0,03 GBq/a for the long-lived, alpha emitting radium, thorium, protactinium, plutonium, americium and curium isotopes;*
- *0,1 GBq/a for the nuclides Se-79, I-129 and Np-237;*
- *0,3 GBq/a for the nuclides C-14, Cl-36 and Cs-135 and for the long-lived uranium isotopes;*
- *1 GBq/a for Nb-94 and Sn-126;*
- *3 GBq/a for the nuclide Tc-99;*
- *10 GBq/a for the nuclide Zr-93;*
- *30 GBq/a for the nuclide Ni-59;*
- *100 GBq/a for the nuclides Pd-107 and Sm-151.*

These constraints apply to activity releases which arise from the expected evolution scenarios and which may enter the environment not until after several thousands of years. These activity releases can be averaged over 1 000 years at the most. The sum of the ratios between the nuclide specific activity releases and the respective constraints shall be less than one."

The release rate constraints have been derived so that they are in general compliance with the dose constraint of 0,1 mSv/a (considering also daughter nuclides), if typical boreal biosphere scenarios are assumed. The rules of application of different kind of scenarios for the release rate criteria are generally the same as those for the dose criteria (as discussed in chapter 3). However, it should be noted that the criteria allow the averaging of the releases over 1 000 years at the maximum. This provides a reasonable time dilution of peak releases, similarly as the risk or expectation value concepts do in case of probabilistic events. It also implies that in the very long term, the most important protection goal is not to try to limit incidental peak releases, albeit they might theoretically imply exposures well above the dose constraint, but to provide an effective overall containment of waste.

Treatment of uncertainties

According to our regulations, the backbone for the demonstration of the compliance with the long-term safety criteria is a scientifically sound, quantitative safety assessment which should be based on a deterministic, conservative approach, whenever practicable. It is, however, recognised that such rigorous quantitative analyses are not always feasible, and therefore the regulations allow some relaxations. The general regulations for safety assessment, quoted in chapter 2, are specified in STUK's guide[2] as follows.

"In order to assess the release and transport of disposed radioactive substances, conceptual models shall first be drawn up to describe the physical phenomena and processes affecting the performance of each barrier. Besides the modelling of release and transports processes, models are needed to describe the circumstances affecting the performance of barriers. From the conceptual models, the respective calculational models are derived, normally with simplifications. Simplification of the models as well as the determination of input data for them shall be based on the principle that the performance of any barrier will not be overestimated but neither overly underestimated.

The modelling and determination of input data shall be based on the best available experimental knowledge and expert judgement obtained through laboratory experiments, geological investigations and evidence from natural analogues. The models and input data shall be appropriate to the scenario, assessment period and disposal system of interest. The various models and input data shall be mutually consistent, apart from cases where just the simplifications in modelling or the aim of avoiding the overestimation of the performance of barriers implies apparent inconsistency.

The importance to safety of such scenarios that cannot reasonably be assessed by means of quantitative analyses, shall be examined by means of complementary considerations. They may include e.g. bounding analyses by simplified methods, comparisons with natural analogues or observations of the geological history of the disposal site. The significance of such considerations grows as the assessment period of interest increases, and the judgement of safety beyond one million years can mainly be based on the complementary considerations. Complementary considerations shall also be applied parallel to the actual safety analysis in order to enhance the confidence in results of the whole analysis or a part of it."

Obviously conservatism in absolute sense is unattainable, given the inherent uncertainties related to the long-term performance of the disposal system. The criteria imply that the result of the analysis (endpoint indicator) with reasonable assurance overestimate really occurring dose or release rate. Our regulations do not explicitly require rigorous quantification of the uncertainties e.g. in form of confidence levels; rather the implications of uncertainties should be illustrated by means of variant and sensitivity analyses and the confidence in the assessments should be enhanced by complementary considerations referred to above. Thus, though the safety criteria are quite unambiguous, compliance with them cannot be deemed in a straightforward way but will involve abundantly expert judgement.

RISCOM II – ENHANCING TRANSPARENCY AND PUBLIC PARTICIPATION IN NUCLEAR WASTE MANAGEMENT

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Project partners: Swedish Nuclear Power Inspectorate, SKI, Sweden; Swedish Radiation Protection Authority, SSI, Sweden; Swedish Nuclear Fuel and Waste Management Co., SKB, Sweden; Karinta-Konsult, Sweden; UK Nirex Ltd, UK; Environment Agency, UK; Galson Sciences, UK; Lancaster University, UK; Électricité de France, EDF, France; *Institut de Radioprotection et de Sûreté Nucléaire*, IRSN, France; Posiva Oy, Finland; Nuclear Research Institute, Czech Republic; Diskurssi Oy, Finland (sub-contractor) and Syncho Ltd, UK (sub-contractor)

Background and objectives

RISCOM II is a project (FIKW-CT-2000-00045) within EC's 5th framework programme, and it was completed in October 2003. The RISCOM Model for transparency was created earlier in the context of a Pilot Project funded by SKI and SSI and has been further developed within RISCOM II. The overall objective was to support transparency of decision-making processes in the radioactive waste programmes of the participating organisations, and also of the European Union, by means of a greater degree of public participation. Although the focus has been on radioactive waste, findings are expected to be relevant for decision making in complex policy issues in a much wider context.

Experiences from the various national radioactive waste management programmes vary and countries are at different stages of developing long-term solutions to their waste problems. There are several examples of significant progress all the way to the siting of a final repository. The siting of radioactive waste installations has, however, also met substantial public opposition in several countries, and it is with this background that the RISCOM II project was initiated.

According to the RISCOM Model, to achieve transparency there must be appropriate procedures in place in which decision makers and the public can validate claims of truth, legitimacy and authenticity. The procedures should allow ***stretching***, which means that the environment of e.g. the implementer (of a proposed project), the authorities and key stakeholders is sufficiently demanding and that critical questions are raised from different perspectives. Accordingly, in RISCOM II the issues are analysed especially with respect to their value-laden aspects and procedures for citizen participation are tested. Furthermore, the impact of the overall organisational structure of radioactive waste management in a country on how transparency can be achieved is investigated.

There are several novel features of the project. First the focus on values in the otherwise very technically dominated area of radioactive waste management, and a multi-disciplinary approach opens new perspectives. Performance assessment (PA) is an important area where this is needed. PA has usually been an expert dominated activity where experts communicate with other experts. The users of PA results were mostly experts or decision makers with expert knowledge. Now, however, the group of users of PA has widened to include members of the public, concerned groups and communities involved in site selection processes. The PA experts thus have to communicate facts and values with stakeholders and decision makers. This project has analysed values in PA and explored statements and arguments from stakeholders, which should influence how future PAs are conducted and communicated with the public. Furthermore, as regulatory standards and criteria set the framework for PA, it is important to open them up for public input.

Summary of conclusions

The project has clarified how the RISCOM Model can best be used in radioactive waste management programmes:

- In parallel with possible further development and refinement of the RISCOM Model, its theoretical grounds in combination with its demonstrated applicability makes it ready for further use directly in radioactive waste management programmes for the design of decisions processes and means for citizen participation.
- In particular, it was shown by hearings organised by SKI and SSI, that the RISCOM Model can be used to support the design of public events and decision processes for the sake of transparency. The hearing format developed using the model was successful in many aspects such as a high level of involvement, the mental separation of structurally different issues and stretching without a too adversarial set-up.

One of the cores issues addressed in the study has been how PA can be made more transparent and accessible to the general public:

- To incorporate the value judgements of stakeholders into PA would include conducting PA by starting from the issues of concern among stakeholders and communicating with them during the PA work.
- PA should not be communicated by information departments – the real experts need to engage themselves so that people can see that they are honest, open about uncertainties and address the concerns of ordinary people.
- Regulatory standards and criteria is one important area where the principles of transparent decision making should be applied. If the authorities involve the citizens at the stage of developing the regulations, this would be a way to include their values into the framework of PA.
- PA must keep its identity as a scientific and engineering enterprise. Engaging in public dialogue must not dilute the science and steer experts away too much from their core activity.

Sometimes there may be unrealistic expectations that public participation should lead to consensus. This project has addressed how transparency relates to consensus building:

- A transparent and democratic decision-making process must not necessarily lead to consensus about a proposed project. Transparency, however, leads to a higher level of awareness of all aspects of the issue, which should be to the benefit of high quality decisions.

There is close relationship between transparency and public participation. The RISCOM Model can help in public participation and what that requires:

- The UK group has developed one set of criteria in the context of testing several dialogue processes.
- Evidence from the UK dialogue processes suggests that the actual use made of information is minimal. This suggests that great care should be taken in targeting information resources where they will be most useful.
- A nuclear waste management programme must have resources to allow for citizen participation. Proper resources will encourage positive engagement, improve decision making and increase public confidence.

UNCERTAINTY GOVERNANCE: AN INTEGRATED FRAMEWORK FOR MANAGING AND COMMUNICATING UNCERTAINTIES

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Introduction

Treatment of uncertainty, or in other words, reasoning with imperfect information is widely recognised as being of great importance within performance assessment (PA) of the geological disposal mainly because of the time scale of interest and spatial heterogeneity that geological environment exhibits. A wide range of formal methods have been proposed for the optimal processing of incomplete information. Many of these methods rely on the use of numerical information, the frequency based concept of probability in particular, to handle the imperfections. However, taking quantitative information as a base for models that solve the problem of handling imperfect information merely creates another problem, i.e., how to provide the quantitative information.

In many situations this second problem proves more resistant to solution, and in recent years several authors have looked at a particularly ingenious way in accordance with the rules of well-founded methods such as Bayesian probability theory, possibility theory, and the Dempster-Shafer theory of evidence. Those methods, while drawing inspiration from quantitative methods, do not require the kind of complete numerical information required by quantitative methods. Instead they provide information that, though less precise than that provided by quantitative techniques, is often, if not sufficient, the best that could be achieved. Rather than searching for the best method for handling all imperfect information, our strategy for uncertainty management, that is recognition and evaluation of uncertainties associated with PA followed by planning and implementation of measures to reduce them, is to use whichever method best fits the problem at hand. Such an eclectic position leads naturally to integration of the different formalisms.

While uncertainty management based on the combination of semi-quantitative methods forms an important part of our framework for uncertainty governance, it only solves half of the problem. Communication of its results with a variety of stakeholders is essential. The concept of "network PA communities" has been developed for this purpose, where members, including ourselves, other stakeholders and interested individuals, are linked through the internet with resources for PA, e.g., PA codes and databases provided on line on demand.

In this paper the underlying concept and framework of our uncertainty management and communication approach is discussed together with example applications.

Uncertainty management – integration of different formalisms

Types of uncertainty

There are a number of studies that have attempted to classify uncertainties associated with PA [1][2]. In the current paper, following the recent work concerning an integrated approach to uncertainty analysis [3], the following classification is adopted;

- vagueness;
- ambiguity;
- chance (variability).

Vagueness can be used to describe certain kinds of uncertainty associated with linguistic or intuitive information. Examples of vague information are that the data quality is "good" or that a rock mass has "low permeability". From a set theoretic point of view, vagueness implies that the boundary of a set is not clearly defined and, thence, it can be treated by introducing membership functions as a means to represent an assessor's belief of containment in a fuzzy set [4]. Fuzzy logic is a many-valued extension of Boolean logic based on the fuzzy set theory in which truth values are continuous function between the endpoints of the interval [0, 1]. The logic operations and associated arithmetic operations are those of conjunction, disjunction, and negation. The min and max operators are used for conjunction and disjunction respectively in fuzzy logic. The law of "excluded middle" in probability theory, i.e. $p(x \vee x') = 1$, where p denotes probability and x' is negation of x, does not hold here.

Ambiguity, on the other hand, lies in the assignment of an element "x" from a universe of discourse X to one or more crisp subsets of X. The crisp subsets have no uncertainty about their boundaries as fuzzy sets do in the case of vagueness. For example, it is not possible to decide whether a missed measurement exceeds unity or not despite the fact that the subset is clearly defined, i.e., $\{x | x > 1\}$. The uncertainty arising from ambiguity is associated with lack of evidence to establish an assignment. Ambiguity can be measured by using a set function $v(A) \in [0,1]$ for $A \subseteq X$ satisfying the following [3];

(i) $A \subseteq B \rightarrow v(A) \leq v(B)$;

(ii) a conjunctive operator $v(A \cap B)$ is associative, commutative and monotonic with identity 1;

(iii) a disjunctive operator $v(A \cup B)$ with identity 0.

A probability measure P satisfies the conditions listed above with;

(1) $P(A \cap B) = P(A|B)P(B) = P(B|A)P(A)$;

(2) $P(A \cup B) = P(A) + P(B) - P(A \cap B)$.

Since ambiguity is not a random notion, the probability measure should be interpreted as the subjective probability rather than the relative frequency. For this reason P can be rewritten as P_s to denote that it is subjective (personal) probability. Hence P_s implies that the assessor is prepared to bet an amount P_s in exchange for 1.

The other candidate is possibility measures Π with;

(3) $\Pi(A \cap B) = \min[\Pi(A), \Pi(B)]$;

(4) $\Pi(A \cup B) = \max[\Pi(A), \Pi(B)]$.

Possibility can be thought of as being complementary to the degree of surprise that a person experiences if an event occurs, as opposed to whether it occurs as a matter of chance. Both probability and possibility measures are generally normal, with $P_s(X) = \Pi(X) = 1$, for a probability measure, this entails additivity $\int_{x \in X} p_s(x) = 1$, while for possibility measures this is $\max_{x \in X} \pi(x) = 1$. Many methods are available to convert a given probability distribution to a possibility distribution, and vice versa. One of the most prominent is the maximum normalisation or ratio scale method [5]. Given a probability distribution $p_s(x)$, then it can be converted to a corresponding possibility distribution

$$\pi(x) = \frac{p_s(x)}{\underset{x \in X}{Max}\ p_s(x)} \; ; \tag{5}$$

so that $\max_{x \in X} \pi(x) = 1$ is asserted. On the other hand, a probability distribution

$$p_s(x) = \frac{\pi(x)}{\int_{x \in X} \pi(x) dx} \; ; \tag{6}$$

may be defined based on a possibility distribution $\pi(x)$ to achieve $\int_{x \in X} p_s(x) = 1$. Possibility theory, with its maximal normalisation which is weaker than probability, is sometimes portrayed as equivalent to fuzzy set theory, and thus possibility measures are presumed to be determined by the same methods of expert elicitation. However possibility measures and fuzzy sets are representations with distinct formal and semantic domains, which should be reflected in the elicitation process. Possibility measures can have significant advantages over the strict use of probability measures in studies such as system reliability [3].

Chance describes the uncertainty in the occurrence of an event, i.e., it is not possible to decide whether the event will or will not occur due to its random nature. Probability based on the relative frequency theory, denoted as p_f, is best suited for measuring chance.

In case that the hydraulic conductivity of a rock mass at a location has a 95% chance of being less than 10^{-10} m/s, there is a 5% chance that it is over 10^{-10} m/s. However, in fact it could be extremely conductive. On the other hand saying that a rock mass at a certain location has a high membership in the set "impermeable" rock, could involve two different types of uncertainty, i.e., vagueness and ambiguity. If the uncertainty is mainly due to fuzziness in the definition of the set "impermeable" rock, then it arises from vagueness. In this case, there is a high likelihood that the rock could still have quite a low permeability even if its conductivity turns out to be more than 10^{-10} m/s. However, if the uncertainty originates from lack of evidence, e.g., no measurement has been made and it is only inferred from the fact that similar rock in an analogous setting has a conductivity less than 10^{-10} m/s, it is due to ambiguity. There is some non-zero membership of not being "low permeability" and, as in the case of uncertainty arising from chance, it could be very conductive. However, there is an important philosophical difference, in that it has already been decided, in this case, whether or not the rock conductivity is over 10^{-10} m/s: it is just unknown. Once the conductivity is measured, the uncertainty due to ambiguity or chance will disappear but vagueness will not.

In most of the situations envisaged in PA, uncertainties from different sources are mixed together. One particularly important example is the mixture of ambiguity and chance, i.e., lack of evidence about the occurrence of events that might occur randomly. In these situations, it is extremely difficult, if not impossible, to obtain evidence to show that the event in question is indeed of a random nature. In other words ambiguity "masks" the nature of the events and processes to be assessed.

Gaines and Kohout [6] distinguish between events E that are "traditionally possible" in that $P_f(A)=\varepsilon>0$ [10] and thus must occur in the limit of infinite time, and those that are not impossible but still need not ever occur. This latter case can be identified as "properly possible". Building from this, it is possible to draw on Zadeh's measure of compatibility between a probability distribution for chance and possibility distribution for ambiguity as

$$(7) \qquad g(p_f, \pi) = \sum_{x \in X} p_f(x)\pi(x).$$

Joslyn **[7]** identified the condition of strong compatibility when $g(p_f, \pi) = 1$, which requires that the possibility is unity wherever the probability is positive. Thus, from this perspective, traditionally possible events, including all events that are actually observed, require total mathematical possibility $\Pi(E)=1$ and positive (frequency-based) probability. However, properly possible events are those such that $\Pi(E)>0$ yet such that $P_f(E)=0$. These are the rare events that are so important in reliability studies of high-consequence systems. As was shown by Joslyn, possibilities becomes probabilities as the information granularity, i.e., ambiguity of the information, becomes more specific if the event in question is indeed of a random nature. This is a very nice feature in modelling ambiguity and chance at the same time in the case where the quantity and quality of information available is improved as time proceeds. However it should be noticed that, in the case of PA, ambiguity seldom diminishes as the timescale of interest is beyond our experience and due to the limited number of measurements of spatial heterogeneity.

Bayesian framework for updating uncertain knowledge

Since there are different types of uncertainty and associated measures, integration of the different formalisms to treat uncertainties is required for the purpose of the uncertainty management. In addition, taking into account the scope of uncertainty management, i.e., recognition and evaluation of uncertainties associated with PA followed by planning and implementation of measures to reduce them, it is essential that a framework for such integration is able to take account of improvements in the available information in order to update the evaluation. As a candidate for such a framework, the Bayesian method as in [3] is employed.

Bayes' rule describes, in light of information *H*, the following relationship among probabilities of events (*X* and *Y*) in terms of conditional probability.

$$(8) \qquad P(X \cap Y; H) = P(Y|X;H)P(X;H) = P(X|Y;H)P(Y;H)$$

By equating the two expressions and rearranging the associated terms,

$$(9) \qquad P(X|Y;H) = \frac{P(Y|X;H)P(X;H)}{P(Y;H)},$$

or alternatively,

$$(9') \qquad P(X|Y;H) \propto P(Y|X;H)P(X;H)$$

10. For traditional probability measure based on the relative frequency, P is denoted as P_f in this paper.

is given. Now, suppose that $Y=y$ has been observed. Then what is the assessor's uncertainty about X; i.e., what is $P(X; y, H)$? Since the assessor has actually observed $Y=y$, the first factor in the right hand side cannot be interpreted as a probability any more. Hence it is called the likelihood function and denoted as $L(X; y, H)$. Using the likelihood function, (9') can be rewritten as

$$(10) \quad P(X; y, H) \propto L(X; y, H) P(X; H).$$

(10) serves as a systematic scheme to update probabilities in light of data. $P(X; H)$ is called the prior probability distribution of X, while $P(X; y, H)$ is called the posterior distribution.

Note that *the likelihood function is not a probability and therefore does not need to obey the law of probability*. It simply connects the two probabilities: the prior distribution and the posterior distribution. The likelihood function is a purely subjective function that enables the assessor to assign relative weights to different values of X. Because of this characteristics of the likelihood function, the Bayesian method can be used to link probability theory with fuzzy logic and possibility theory. Specifically, probability measures relate to fuzzy sets and possibility measures through the membership functions. The associated membership function can be interpreted as a likelihood function since the process of defining a membership function is subjective in nature and the membership functions are nonnegative. Then for a given probability-based prior distribution, the membership functions, as likelihoods, can be used to produce a probability-based posterior distribution. An example of application of this approach to average hydraulic conductivity of a rock mass is depicted in Figure 1.

Integration of uncertain information

Defining a likelihood function is a subjective exercise reflecting the assessor's opinion. For the problems with incomplete, imprecise and/or inconsistent information where conditional probabilities cannot be supplied or rationally formulated, a possibility-based approach offers a structured methodology to eliciting expert judgement and reflecting it into the likelihood function. In what follows two examples of such an approach are illustrated.

Derivation of a possibility distribution using evidence theory

The safety case relies partly on the stability of the geological environment and the long time scale associated with flow and transport through the geosphere. A conceptual site model integrates numerous types of information into an internally consistent understanding of these features. The model then rationalises quantitative safety analyses and develops complementary, often qualitative, arguments that support the safety case. A systematic treatment is required to integrate all the relevant geological information to form a representation of the geological environment and its evolution. The approach illustrated here is based on Evidential Support Logic (ESL) [8], which is a generic mathematical concept based on the evidence theory and consists of the following key components.

Suppose a proposition is formed by integrating and interpreting a number of information items from different sources. The first task of ESL is to unfold this proposition by constructing a process model. The "top" proposition is subdivided iteratively to form an inverted tree-like structure, with propositions at each lower level corresponding to intermediate interpretations. The subdivision is continued until the original information is reached.

After constructing the process model, confidence in the top proposition is evaluated. The degree of confidence in the support for each lowest-level proposition from corresponding information (i.e.

evidence) is estimated in terms of the interval probability and propagated through the process model using simple arithmetic (see Appendix). Interval probability, unlike the conventional "point" probability, defines an upper- and a lower-bound for the probability of a proposition A to be true, $\underline{P_s}(A) \le P_s(A) \le \overline{P_s}(A)$. Then $\underline{P_s}(A)$ and $\overline{P_s}(A)$ do not follow the theory of probability, i.e., $\overline{P_s}(A) + \overline{P_s}(A^c) > 1$, $\underline{P_s}(A) + \underline{P_s}(A^c) < 1$ where A^c denotes negation of A. In fact it has been shown that $\overline{P_s}(A)$ can be identified as the possibility of the proposition A being true while $\underline{P_s}(A)$ can be regarded as the necessity of the proposition A being true, i.e., complementary to possibility of A being false (Figure 2). Thus interval probability is an expression equivalent to possibility measures.

Figure 1. **Bayesian framework for updating uncertain knowledge using possibility-based likelihood function**

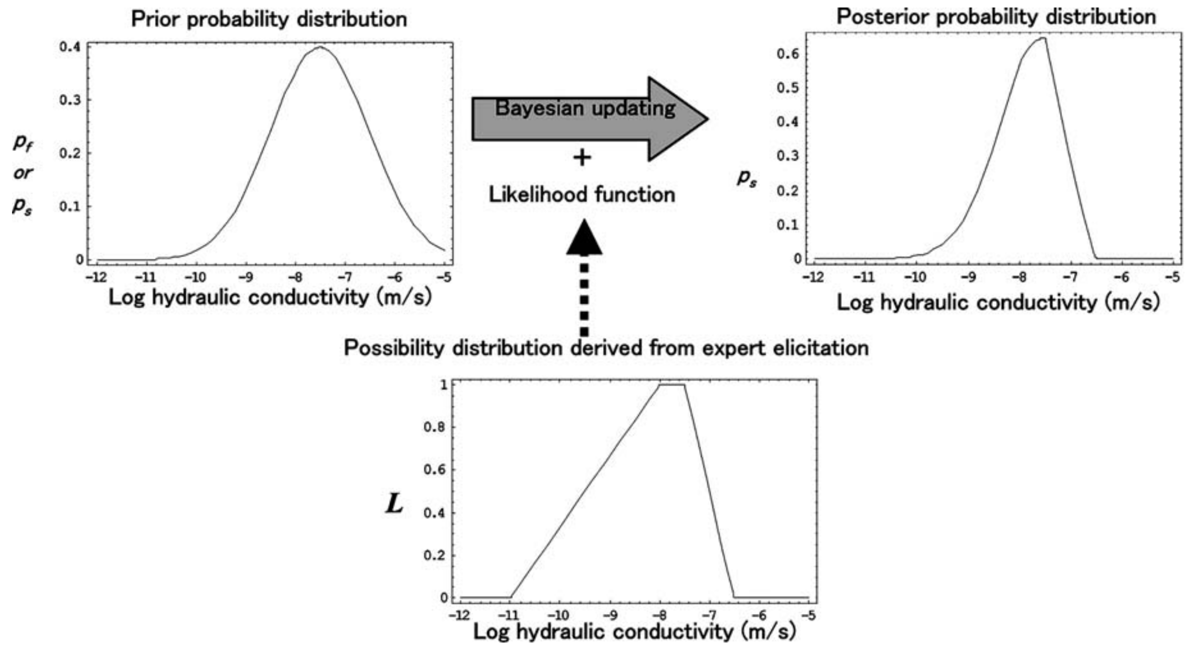


Figure 2. **Interval probability and possibility measures**

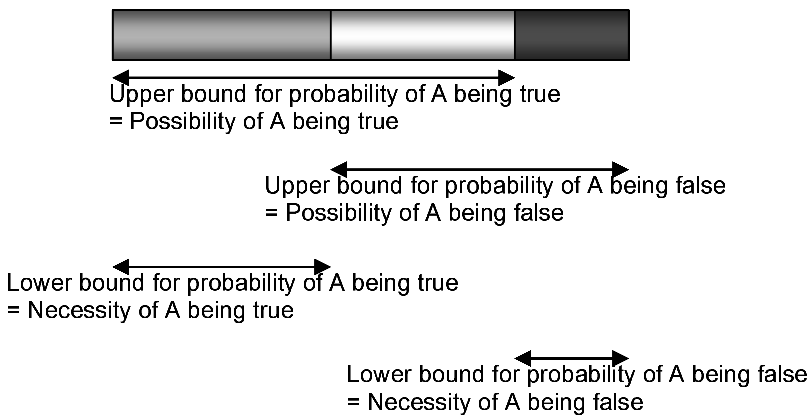


Figure 3. **Example of a process model constructed to evaluate degree of confidence in stability of the current saline-fresh water interface**

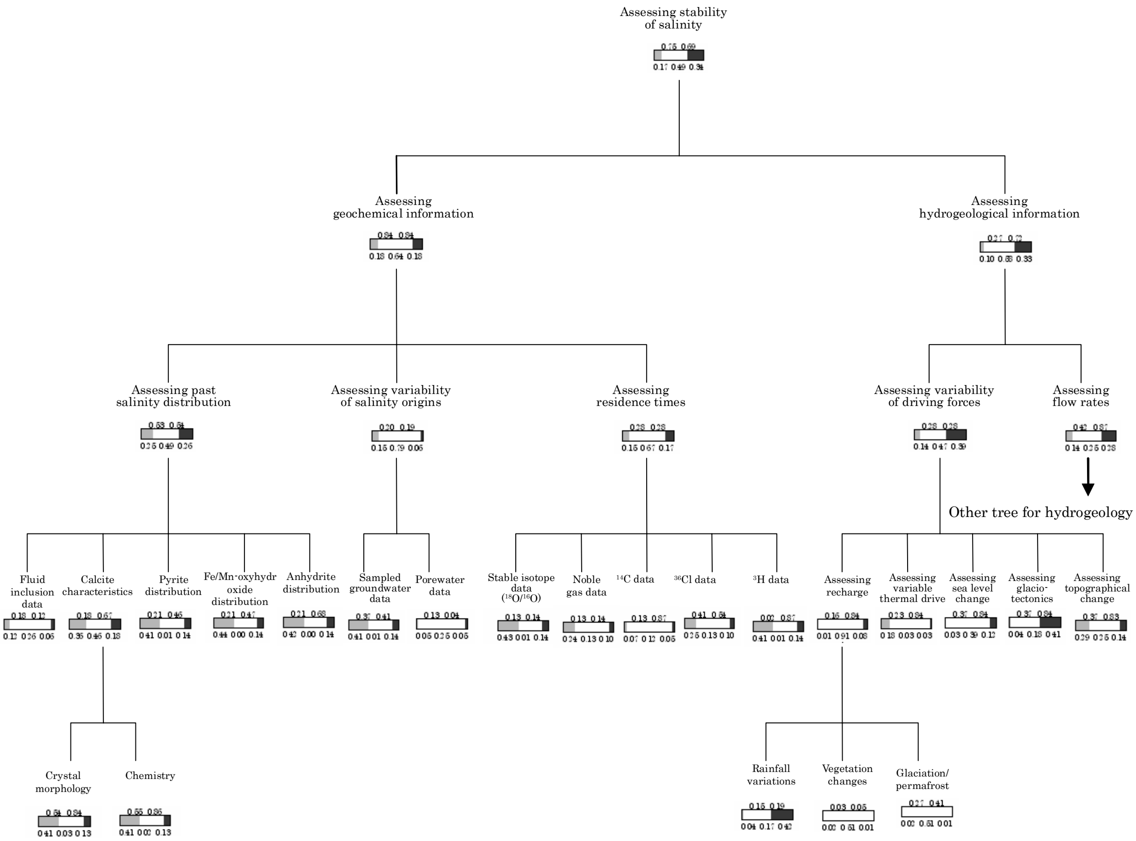


Figure 3 illustrates an example process model to evaluate the degree of confidence that a variety of evidence from a hypothetical site supports the stability of the current saline-fresh water interface.

The process model represents a logical structure that supports a conceptual site model, or its components, based upon available geological information. The degrees of confidence that the propositions at various levels are supported by evidence illustrates how uncertainties of various (multi-disciplinary) origins are propagated through the process model. Thus, use of ESL could increase the transparency and traceability of the underlying reasoning behind a conceptual site model. In turn this increase in clarity would expedite the communication of confidence and understanding of the geological environment and its evolution. In addition to this, a "ratio plot" (Figure 4) can be used to summarise and compare confidence in a number of competing conceptual model options. The *y*-axis of the ratio plot is $\log[p/q]$ and the *x*-axis is *u*, where *p* (*q*) is the minimum degree of confidence that the model option is supported (not supported) and *u* is the uncertainty associated with the evaluation. Hence a model option with stronger relative support ($\log[p/q]$) and one with greater uncertainty correspond to larger *y*- and *x*-coordinates respectively. By locating the competing model options in the ratio-plot, their characteristics can be summarised graphically and compared.

Construction of the process model and evaluation of confidence should be carried out iteratively as the siting process proceeds. To support planning of the next stage of site characterisation, it is useful to classify the importance of different types of evidence by sensitivity analyses. In the case of

ESL, this can be done by calculating the reduction in the uncertainty associated with the top proposition assuming that uncertainty in each piece of evidence vanishes in turn (Figure 5). The results of the analysis can then be used as an input to prioritise further data acquisition.

Figure 4. **Example of a "ratio plot"**

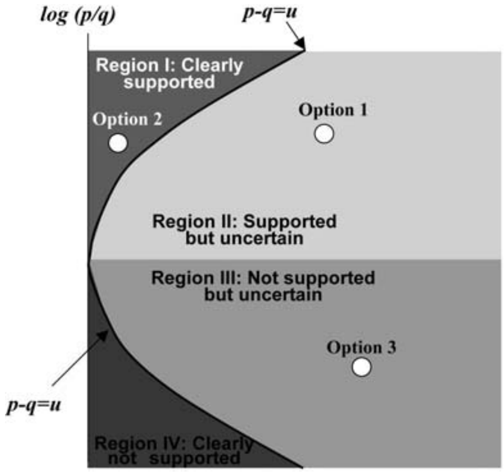
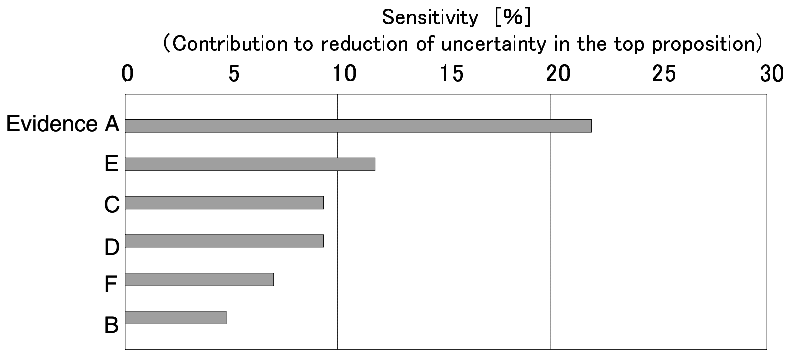


Figure 5 **Example of sensitivity analysis**



Aggregation of possibility distributions

Uncertainty involved in PA, i.e., non-unique choice of scenarios, models and parameter values, originates from a number of different sources and it is often necessary to decompose it into different factors. For example, *Kd* value for Cs to be used in PA could be associated with the following uncertain factors;

- uncertainty related to whether the current hydrogeological condition remains or change significantly;
- uncertainty related to the average salinity under present conditions;
- uncertainty related to the average salinity after the current hydrogeological conditions change;
- uncertainty related to *Kd* value at a given salinity level.

Let $\pi(H_0)$ be the possibility of current hydrogeological conditions remain unchanged, and $\pi(H_1)$ be the possibility that the saline front moves substantially [Figure 6 (a)]. These quantities could be estimated by using ESL analysis as illustrated in the previous section. Similarly we define $\pi(H_0, S_-), \pi(H_0, S_0)$ and $\pi(H_0, S_+)$ as the possibilities of salinity being "low", "intermediate" and "high" under current condition respectively, $\pi(H_1, S_-)$, $\pi(H_1, S_0)$ and $\pi(H_1, S_+)$; possibility of salinity being "low", "intermediate" and "high" provided the saline front moves substantially in future (Figure 6 (b)). Then the possibility of future salinity can be estimated by using the "Min-Max" rule as follows;

$$
\begin{aligned}
(11) \quad & \pi(S_-) = Max[Min(\pi(H_0, \pi(H_0, S_-))), Min(\pi(H_1, \pi(H_1, S_-)))], \\
& \pi(S_0) = Max[Min(\pi(H_0, \pi(H_0, S_0))), Min(\pi(H_1, \pi(H_1, S_0)))], \\
& \pi(S_+) = Max[Min(\pi(H_0, \pi(H_0, S_+))), Min(\pi(H_1, \pi(H_1, S_+)))],
\end{aligned}
$$

where $\pi(S_-), \pi(S_0)$ and $\pi(S_+)$ denote the possibilities of the salinity in the future being low, intermediate and high respectively.

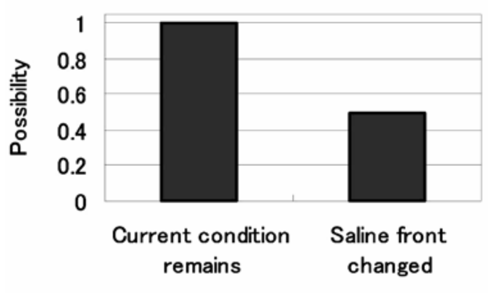
Suppose a possibility distribution of *Kd* values for Cs is estimated from the results of sorption experiments at low, intermediate and high salinity levels $\pi(S_-, Kd(x)), \pi(S_0, Kd(x))$ and $\pi(S_+, Kd(x))$, (Figure 6 (c)). Then the possibility distribution of the *Kd* being *x*, $\pi(Kd(x))$, can be estimated by the following equation;

$$
(12) \quad \pi(Kd(x)) = Max[Min(\pi(S_-), \pi(S_-, Kd(x))), Min(\pi(S_0), \pi(S_0, Kd(x))), Min(\pi(S_+), \pi(S_+, Kd(x)))].
$$

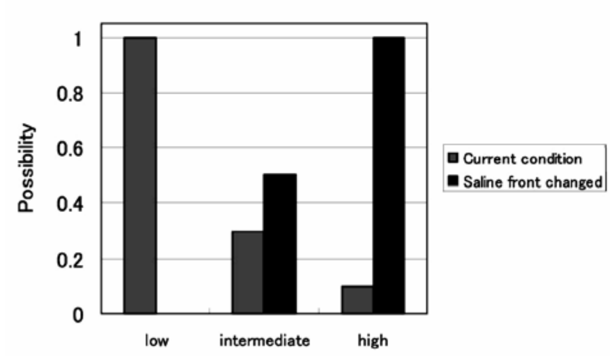
(11) and (12) can also be formulated in terms of fuzzy relations and their composition **[3]**.
Figure 6 (d) shows $\pi(Kd(x))$ calculated by applying (11) and (12).

Figure 6. **Aggregation of possibility distributions for Cs *Kd* value taking a number of uncertain factors into account**

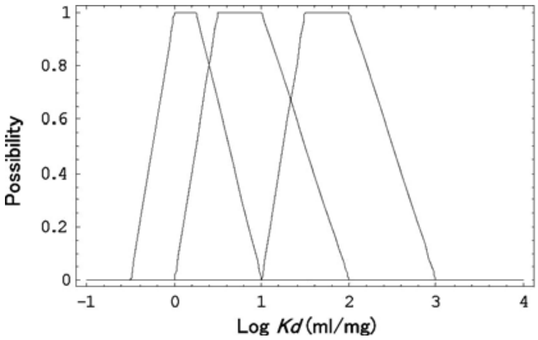
(a) Uncertainty related to stability of current conditions



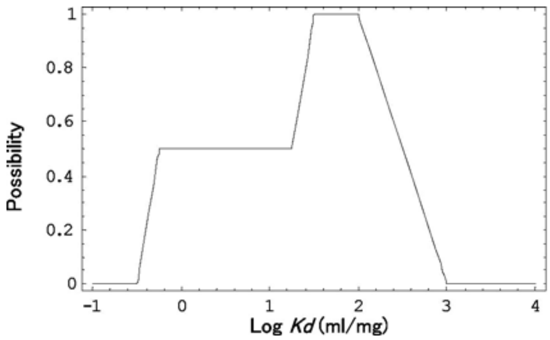
(b) Uncertainty of salinity under future given conditions



(c) Uncertainty of Cs *Kd* under given salinity levels



(d) Overall uncertainty of *Kd* to be used in PA



Uncertainty in system performance assessment

The compatibility between probabilistic and possibilistic approaches for treating uncertainty provides flexibility to system performance assessment. For example, the application of the probabilistic approach to handling conceptual uncertainties associated with selection of scenarios and model options, suffers from the philosophical difficulty of assigning probability to known options since there always remains the possibility that other unknown options exist. Thus it is not possible to define the cumulative probability of the known options, which might be significantly less than unity. In these circumstances, possibility theory can provide practical measures to treating uncertainties.

Another important aspect is related to interdependence between two or more uncertainties. There are a number of uncertain factors associated with PA for multi-barrier systems. If the correlation between these uncertain factors was known, then it could be incorporated in terms of conditional probabilities to formulate the problem in the probabilistic framework. In reality, however, sufficient information about the correlation between these factors does not typically exist. Let *a* and *b* be a measure for uncertainty due to ambiguity and/or chance. Then, by denoting the conjunction of *a* and *b* by $f(a,b)$, both $f(a,b)$ itself and $g(a,b)=a+b-f(a,b)$ have to be associative. The general formula satisfying this requirement is given by,

$$f(a,b)=\log_s\left[1+\frac{(s^a-1)(s^b-1)}{s-1}\right], \tag{13}$$

where $s\in[0,1]$ is a constant and is called Frank's *t*-norm [9]. $f(a,b)$ in (13) approaches multiplication ab asymptotically as $s\to 1$ and $Min(a,b)$ as $s\to 0$. This implies that it is possible to bound the uncertainty originating from the lack of information on interdependence of uncertain factors by the estimates based on probabilistic and possibilistic approaches. To illustrate the above idea, an example is presented in what follows.

A multi-barrier system consisting of;

- glass waste form that dissolves congruently with a dissolution rate constant over time;
- canister that contains the waste form for approximately 1 000 years to avoid its contact with groundwater;
- bentonite buffer whose hydraulic conductivity is low enough to keep the groundwater flow rate through it negligible compared with transport by diffusion;

- host rock that can be regarded as a continuum and the nuclide transport through it takes place along a one dimensional uniform path;

is considered.

The corresponding nuclide transport model is shown schematically in Figure 7, where the diffusion equation in the one-dimensional cylindrical coordinate in the buffer is combined with the advection-dispersion equation in the Cartesian one-dimensional coordinate in the host rock via a mixing cell representing the excavation disturbed zone.

Furthermore it is assumed that the glass dissolution time has the uncertainty shown in Figure 8. The possibility distribution in Figure 8 is derived from expert elicitation and the corresponding probability distribution is obtained by the maximum normalisation (5). It is also assumed that the hydraulic conductivity of the host rock and the *Kd* of Cs exhibit the uncertainty depicted in Figures 1 and 6 respectively. Either the probability distribution or the equivalent possibility distribution, which are exchangeable via equations (5) and (6), is used depending on the type of analysis, i.e., probabilistic or possibilistic. For simplicity, input values for the other parameters are fixed as in Table 1.

Results obtained by probabilistic and possibilistic approaches for normalised release rate of Cs-135 from the geosphere are compared in Figure 9 together with the uncertainty bounds. Figure 10 summarises the complementary cumulative probability distribution, $P(x)$, and the complementary cumulative possibility distribution, $\Pi(x)$, defined by,

$$(14) \qquad P(x) = \int_x^{\infty} p(x)dx\,;$$

$$\Pi(x) = \underset{y \geq x}{Max}[\pi(y)].$$

The area bounded by $P(x)$ and $\Pi(x)$ illustrates the size of the uncertainty originating from lack of information on the interdependence of uncertain factors as a function of time. The results are presented in a disaggregated manner in Figure 10, i.e., calculated consequence and its plausibility in terms of probability or possibility are shown separately. In contrast to the case of the properly possible events (see the next section), this mode of presentation seems more adequate since difference in the implication of probabilistic and possibilistic approaches is more evident here.

Figure 7. **Nuclide transport model for system performance assessment**

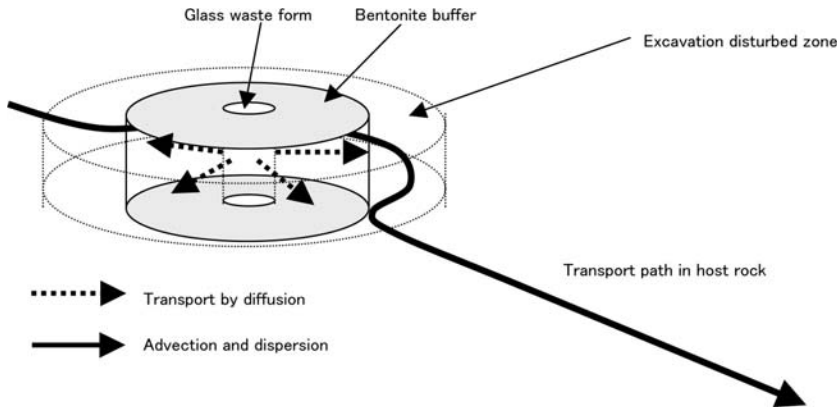


Table 1. **Input parameter values for the example calculations**

Buffer thickness (m)	1	Transport distance through host rock (m)	100
Effective diffusion coefficient in buffer (m^2/s)	0.01	Effective porosity of host rock (-)	0.2
Porosity of buffer (-)	0.4	Density of host rock (kg/m^3)	2700
Density of buffer (kg/m^3)	2700	Hydraulic gradient (-)	0.01

Figure 8. **Probability distribution and possibility distribution of glass dissolution time**

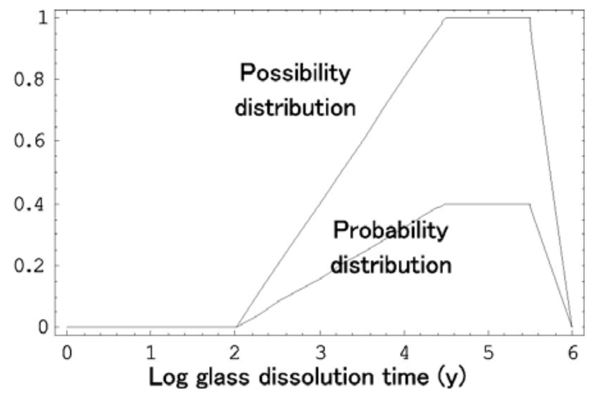
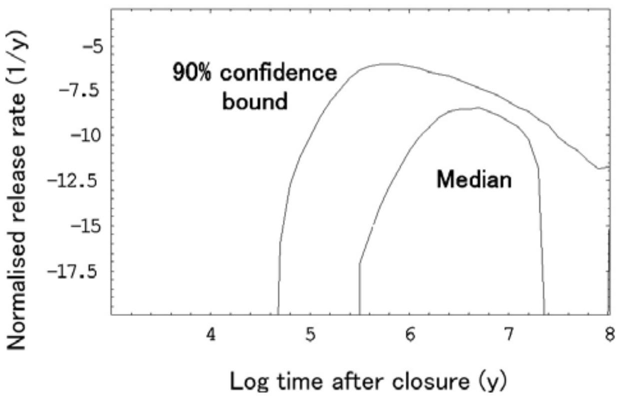


Figure 9. **Probabilistic and possibilistic uncertainty bound for normalised release rate of Cs-135 from geosphere**

(a) Probabilistic



(b) Possibilistic

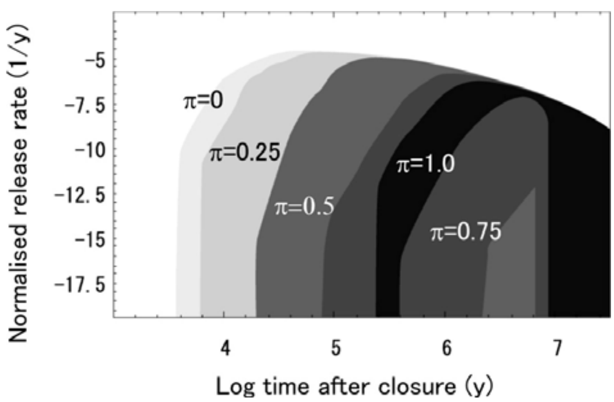
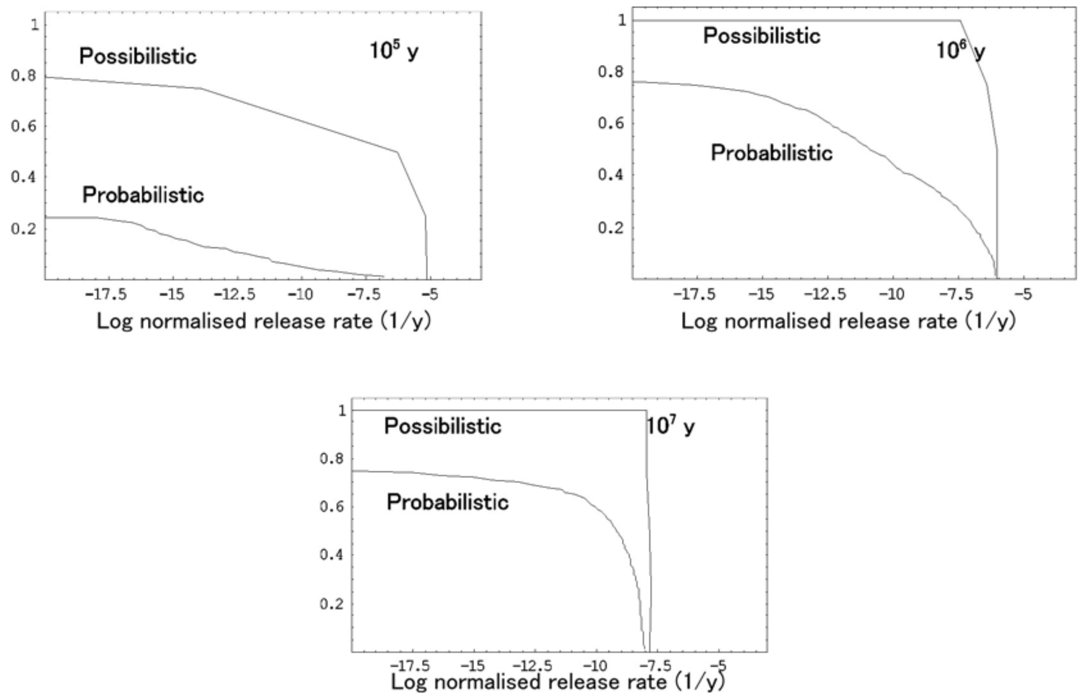


Figure 10. **Comparison of probabilistic and possibilistic complementary cumulative distributions**



Probability of occurrence of properly possible events

As was stated in section "*Types of uncertainty*", it is important to distinguish between events E that are "traditionally possible" in that $P_f(E)=\varepsilon>0$ and thus must occur in the limit of infinite time, and those that are "properly possible", i.e., they are not impossible but still need not ever occur. The properly possible events are those such that $\Pi(E)>0$ yet such that $P_f(E)=0$. These are the rare events that are so important in reliability studies of high-consequence systems.

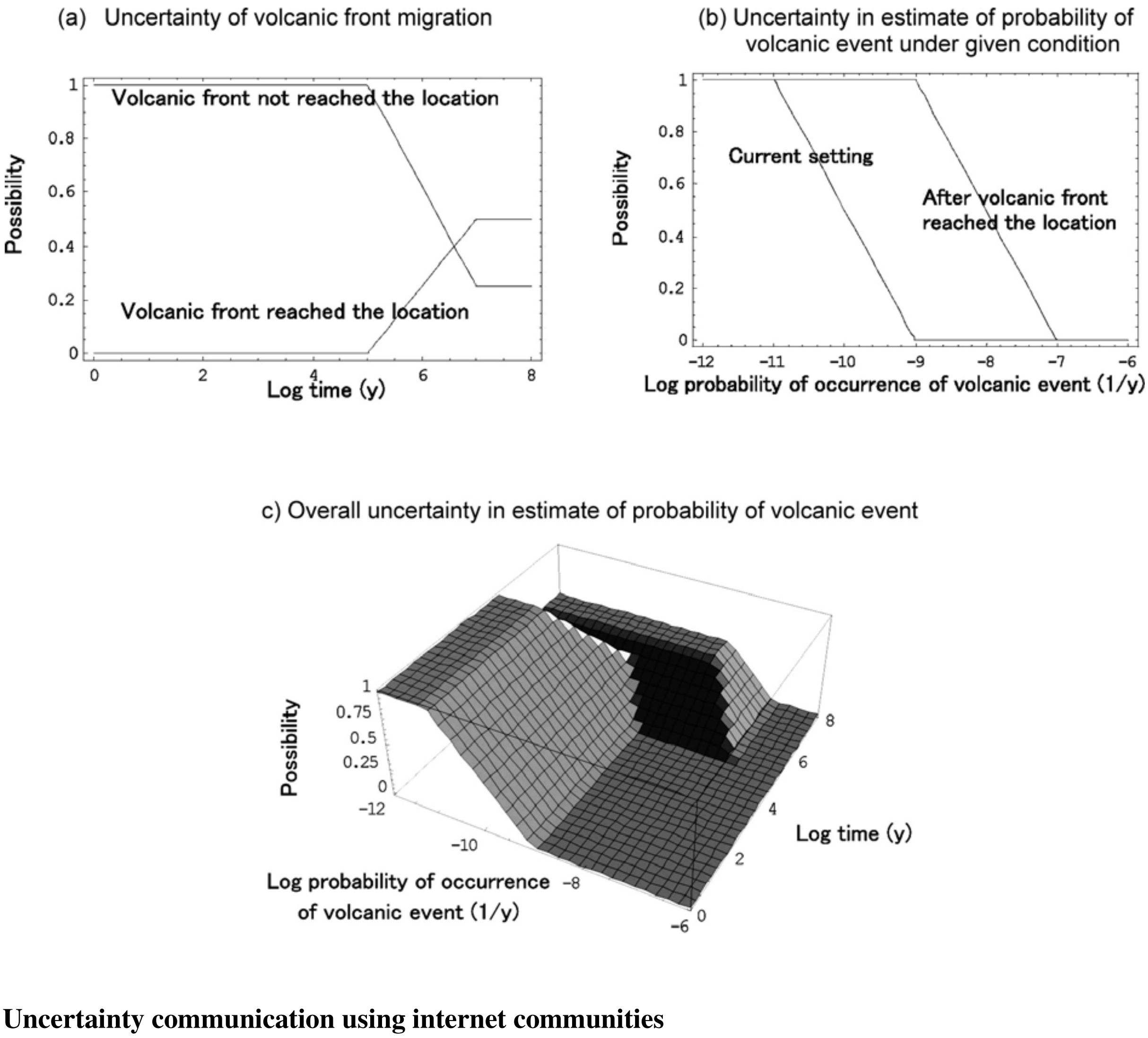
The key to the assessment of the properly possible events is in assigning some non-zero (subjective) probability of occurrence, $P_s(E)>0$. For this purpose, it is useful to express uncertainty in the estimate of $P_s(E)$ in terms of possibility distribution. This idea goes in parallel to "probability of fuzzy events" in [10].

By regarding the probability of occurrence as a fuzzy set described by a possibility distribution, the techniques described in section "*Integration of uncertain information*" can be applied. For example, probability of occurrence of a volcanic eruption at a location which is away from the current volcanic front can be estimated by aggregating the following uncertain factors;

- the possibility that the volcanic front will have migrated and reached the location by time t, $\pi(t)$;
- the "possibility of probability of occurrence" of a volcanic eruption at the location before and after the volcanic front reaches the location, $\pi_0(p_s)$ and $\pi_1(p_s)$.

The possibility $\pi(t)$ can be derived based on a knowledge of the range of the volcanic front migration rate, whereas $\pi_0(p_s)$ and $\pi_1(p_s)$ can be estimated through assessing the range of frequencies of volcanic events in areas where those events have actually occurred in the past. By applying the procedure as in section "*Aggregation of possibility distributions*" the overall uncertainty of $P_s(E)$ in terms of possibility distribution $\pi(t, p_s)$ (Figure 11) can be derived. Product of $\pi(t, p_s)$ and the potential consequence of an volcanic event can be regarded as the possibility distribution of risk concerning the volcanic eruption, which combines the uncertainties arising from ambiguity and chance.

Figure 11. **Aggregation of uncertain factors into the estimation of the probability of a volcanic event**



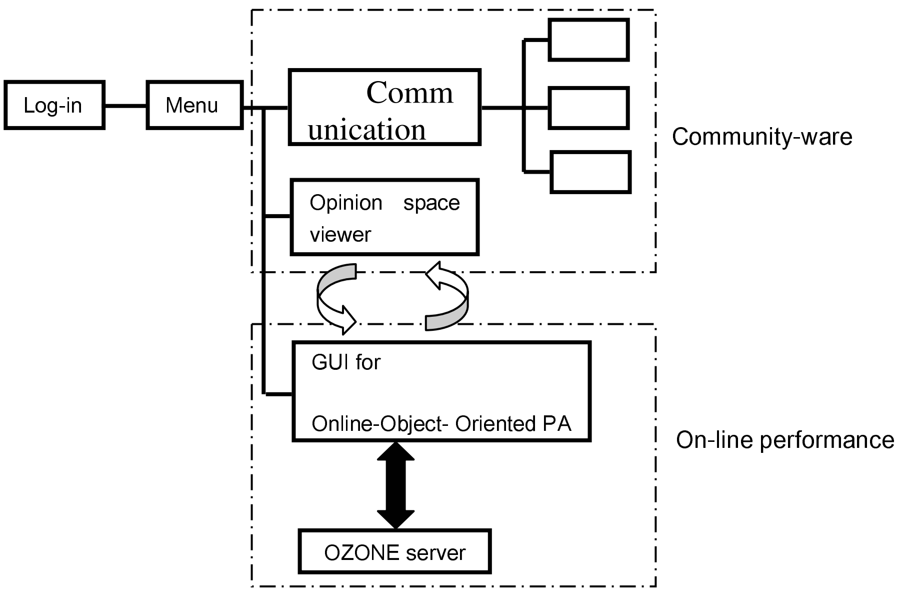
Uncertainty communication using internet communities

While uncertainty management based on the combination of the various formalisms forms an important part of our framework for uncertainty governance, it only solves a half of the problem. It is needed to communicate safety assessment results to a variety of stakeholders. Decisions concerning geological disposal necessitates an underlying knowledge concerning long-term safety. Unlike information, however, knowledge is strongly linked with beliefs and commitment which can only be obtained through experience of the individuals. Hence, in addition to transmitting the results of our uncertainty analysis to stakeholders, interested individuals are encouraged to create their knowledge based on the provided information but, at the same time, independent from implementors' beliefs and commitment. This can be achieved by members of voluntary communities exchanging information, finding partners to collaborate with, and conducting their own PA and uncertainty analysis. Key to this approach is the concept of “network PA communities” as shown in Figure 12, where members are linked through internet with resources for PA, e.g., PA codes and databases, are provided on line on demand [11].

A voluntary PA community to test validity of this approach has been initiated [12]. For this purpose, issues other than the quantitative PA calculations have to be addressed as well. To expedite such activities, a “community-ware” has been developed so that members of PA network communities can grasp their relative positions in an “opinion space” and find possible partners to collaborate with, and allow newcomers to recapture a summary of the previous discussions. In addition, the history of past discussions together with the results of iterative PA calculations will, from time to time, provide useful insight for understanding and modelling the process of consensus building.

From the point of view of uncertainty analysis, PA calculations carried out by numerous individuals through network communities provides a chance to explore “possible” evolutions of the system and the resulting radiological consequences in an exhaustive manner. Furthermore discussion on the individual results among the members of communities, via challenging and defending the assumptions in the PA calculations done by other members, will support the developing knowledge on the safety of the disposal system and the associated uncertainty.

Figure 12. **Structure of the on-line performance assessment community system**



Conclusion

To manage the uncertainties from various sources associated with PA for geological disposal, a number of mutually complementary methodologies have been applied. These are based on various formalisms such as probability theory, Bayesian theory, possibility theory, and evidence theory. In addition a framework has been developed so as to allow implementors to integrate a number of different formalisms to form an eclectic approach to the variety of uncertainties envisaged in PA. Application of this approach to a number of examples have also been illustrated.

To communicate the understanding of the types and sizes of the uncertainties in PA to a variety of stakeholders, an approach utilising PA network communities is proposed, where members exchange information, find collaboration partners, and conduct their own PA and uncertainty analyses. In this way, communities can create their own knowledge based on the provided information but which at the same time is independent from our beliefs and commitment. This approach may play a complementary role to the conventional presentation of PA results.

Reference

[1] NEA (1987), *Uncertainty Analysis for Performance Assessments of Radioactive Waste Disposal Systems*, Proceedings of an NEA Workshop, OECD, Paris.

[2] European Commision (1995), Review on development of methodologies for modelling with uncertainty and variability: Munvar project, EUR16174EN.

[3] Ross, T.J., J.M. Booker and W.J. Parkinson (2002), Fuzzy logic and probability applications; Bridging the gap, Society for industrial and applied mathematics, Philadelphia.

[4] Zadeh, L. (1976), The concept of a linguistic variable and its application to approximate reasoning: Part 3, Inform. Sci., 9, pp.43-80.

[5] Klir, G. (1990), Developments in Uncertainty Based Information, Advanced in Computors, Academic Press, pp.255 – 322.

[6] Gaines, B.R. and L.J. Kohout (1976), The logic of automata, Internat. J. Gen. Systems, 2, pp. 191-208.

[7] Joslyn, C. (1997), Distributional Representations of Random Interval Measurements, Uncertainty Analysis in Engineering and Sciences: Fuzzy Logic, Statistics, and Neural Network Approach, Kluwer Academic Publishers, pp. 37-52.

[8] Hall, J.W., D.I. Blockley, J.P. Davis (1998), Uncertain inference using interval probability theory, International Journal of Approximate Reasoning, 19, pp.247-264.

[9] Frank, M.J. (1979), On the simultaneous associativity of F(x,y) and x + y – F(x,y), Equations Math, 19, pp. 194-226.

[10] Zimmerman, H.-J. (2001), Fuzzy set theory and its applications, 4th edition, Kluwer Academic Publishers.

[11] Takase, H., M. Inagaki and T. Noguchi (2003), Development of an on-line performance assessment system, Proceedings of ICEM'03: The 9th International Conference on Radioactive Waste Management and Environmental Remediation.

[12] Tanaka, H., H. Yokoyama, H. Kimura and H. Takase (2004), Social Technology for Nuclear Safety (XIII): Development of Community-ware for Performance Assessment of HLW Disposal, Proceedings of the Atomic Energy Society of Japan, Spring Meeting, (in Japanese).

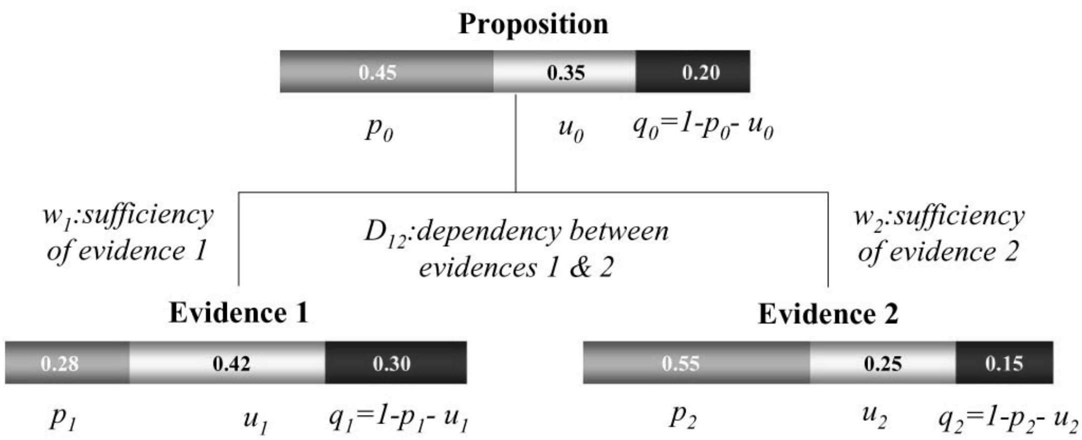
Appendix

The degree of confidence that some evidence supports a proposition can be expressed as a subjective probability. However, since evidence concerning a complex system is often incomplete and/or imprecise, it may be inappropriate to use the classical (point) probability theory. This theory cannot account for uncertainty in an actual evaluation of support, because if some evidence supports a proposition with probability p, the probability against the proposition is automatically $1-p$. For this reason ESL uses the interval probability theory, which allows us to say "the degree of confidence that evidence supports the proposition lies between p and $p+u$". In this case, the degree of confidence that evidence does not support the proposition is between $1-p-u$ and $1-p$. Hence the following items are derived (Figure A):

- the minimum degree of confidence that some evidence supports the proposition is p;
- the minimum degree of confidence that some evidence does not support the proposition is $1-p-u$;
- the uncertainty is u.

The arithmetic used to propagate degrees of confidence upward through the process model is depicted in Figure A, where "sufficiency" of an individual piece of evidence or lower level proposition can be regarded as the corresponding conditional probability. That is, "sufficiency" is the probability of the higher level proposition being true provided each piece of evidence or lower level proposition is true. A parameter called "dependency" is introduced to avoid double counting of support from any mutually dependent pieces of evidence.

Figure A. **Evaluation of confidence using interval probability theory**



$$p_0 = w_1 \; p_1 + w_2 \; p_2 - \rho_{12} Min(w_1 \; p_1 \;, w_2 \; p_2 \;)$$

$$q_0 = w_1 \; q_1 + w_2 \; q_2 - \rho_{12} Min(w_1 \; q_1 \;, w_2 \; q_2 \;)$$

where $$\rho_{12} = \frac{(1-D_{12})(w_1 \; p_1 \; w_2 \; p_2 \;)}{Min(w_1 \; p_1 \;, w_2 \; p_2 \;)} + D_{12}$$

WORKING GROUP 1

RISK MANAGEMENT AND DECISION MAKING

DISCUSSION OF RISKS IN THE CONTEXT OF THE ENVIRONMENTAL IMPACT ASSESSMENT OF THE SPENT FUEL REPOSITORY IN FINLAND

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Introduction and context

In May 1999 Posiva submitted an application for the so-called Decision-in-Principle (DiP) on the final disposal facility of spent fuel to the Finnish Government (Posiva, 1999a). In this application Posiva proposed that the spent fuel from the Loviisa and Olkiluoto nuclear power plants should be disposed of in a KBS-3 type final repository which would be built at Olkiluoto near the Olkiluoto power plant site. According to the Nuclear Energy Act the main purpose of the DiP is to judge whether the facility is in line "with the overall good of society". In doing the judgement the Government – and later the Parliament – should pay particular attention to the alternatives of the proposed project, including the "zero alternative", i.e. the alternative of not realising the project.

The Government approved Posiva's application in December 2000 and the decision was ratified by the Parliament in May 2001. The next major milestone will now be the construction licence, the application for which is planned to be submitted in the early 2010s.

The basis for the Decision-in-Principle application was laid in the report from the Environmental Impact Assessment (EIA) procedure that was started in 1997 and completed in May 1999 (Posiva, 1999b). It was decided that the EIA programme would focus on the issues and concerns that various stakeholder groups find of greatest importance. Consequently, while safety issues played a central role in the early phases of the EIA process, later the focus was more and more shifted to discussion of alternatives, and the comparison of alternatives was given a significant role in the EIA report and the application for DiP. In practice this meant that instead of discussion of the absolute risks of geologic disposal the focus was placed on the relative risk of the proposed project vs. the zero alternative.

Programme formulation

To identify the issues that the various stakeholder groups considered as most important for the EIA Posiva started a major campaign of public interaction, first in the candidate site municipalities, later also nation-wide. As expected, safety issues were usually raised as primary concerns at meetings with the public; it was probably also behind the concerns about *local image*: a central topic of discussion was whether the public image of the municipality would be spoilt if the municipality accepted the siting of the repository. However, as regards safety the concerns were slightly different depending if the question was about the long-term safety of disposal, the operational safety of the disposal facility or the safety of spent fuel transportation. As regards the operational safety and the safety of spent fuel transportation people were interested in the expected radiation levels and consequences of accidents, whereas concerning the long-term safety the main issues seemed to be whether anything at all can be said about that, whether the long-term safety assessments deserve any credibility.

The site selection process for the spent fuel repository was started already in the early 1980s. In parallel to site investigations a research programme into long-term safety was established. For the EIA process the research, development and site investigations activities were extended to address the questions the stakeholders held as important. This meant, in particular, new research into social, socio-economical and socio-psychological aspects of the project and also new studies on the operational and transportation safety.

Shifting emphases

As the EIA process progressed the discussion was more and more shifted from basic issues of safety to wider aspects of the disposal project and its alternatives. In their comments on the EIA programme The Ministry of Trade and Industry recommended that more attention should be given to the assessment of alternatives – even to those alternatives that were not legally available at present. Accordingly, Posiva prepared a structured assessment of the alternatives proposed for the high-level waste management. The assessment was made in three stages: first the broad alternatives including space disposal and other exotic proposals, secondly a comparison of the options that were considered realistic and finally a comparison of the reference alternative (the proposed project) and the zero alternative. At the final stages of the Parliament discussion of the DiP the alternatives came on top of the agenda: while the safety aspects were still questioned, the main comparison was between the risk of long-term interim storage (with wait-and-see attitude on permanent solutions) and the risk of geologic disposal. Two risk scenarios were contrasted: on the one hand, the scenario of an abandoned interim storage of spent fuel; on the other hand a leaking underground repository.

Similarly, at the local level of the candidate municipalities the main discussion moved to the question of what the local community would gain and what it would lose if it chose to accept the siting. Instead of risks it was more often than not the concern about *bad image* that was seen as the main negative impact. A clear distinction was also discernible between the candidate municipalities: the people of those candidate municipalities that had nuclear power plants in their area understood that the spent fuel already existed and was being stored, and the repository would mainly mean bringing the spent fuel from the surface storages to underground repositories; for the other municipalities the project would mean more essential changes. This distinction turned out to be important for the public opinion.

Scholarly critique

The Finnish EIA obtained a lot of interest from the social scientists and several studies have been made in which the process is critically reviewed. Several scientists noticed the shift of emphasis in the public discussion. Some of them described this as surprising and ungrounded and suggested that it was in fact Posiva who wanted to lead the discussion from thorny problems of safety to an area in which the arguments could be more in favour of the proposed project.

For Posiva the shift in emphasis was, indeed, welcome because it meant that the discussion was focused on the real decision-making situation: the DiP was not to judge if disposal would be safe or not, but it would answer the question whether Posiva should continue with preparing for the disposal and concentrate the site investigations on Olkiluoto. However, it was the public criticism and the official statements about the EIA programme that brought about the shift in emphasis, not Posiva’s original proposal for the EIA programme that gave only a rather brief discussion of alternatives.

Lessons learned on risks

The experience obtained from the discussion around the EIA and DiP in Finland can be summarised in the following theses:

- Risk as a quantitative mathematical or engineering entity is not interesting to laymen. For laymen *risk* means primarily the possibility that a certain action may entail negative consequences.
- Outside the community of "risk professionals" the risks can mainly be discussed in terms of consequences and management of the scenarios that may lead to negative consequences; the modalities can only be discussed in qualitative terms, and even then the calibration of such qualitative descriptions may be difficult.

As a corollary to these theses it follows that for the stakeholder decisions on nuclear waste disposal quantitative risk estimates are of little value; more important is how much scope the decisions will leave for future action.

In what follows the theses are explained in more detail.

The problems of the mathematical risk concept come at two levels: First, the justification for the risk formula in which the probability and the consequence are in symmetric positions is questioned. For laymen, the quality of consequences is important and cannot be simplified to a number of deaths or other similar simple measures. Secondly, low or high probabilities can be distinguished by almost anyone, but when it comes to giving a numerical value to a "small" probability the answers may differ over an order of magnitude. So a small probability means completely different things for different persons. The same holds for other proposed measures of uncertainty and the problem is valid for laymen and professionals alike.

People are interested in risk scenarios. In discussing the risks of continued interim storage many people referred to news about collapsing societal systems in countries where such situation some years ago was still hardly imaginable. People also had an idea about the consequences of unguarded, uncontrolled storages of highly radioactive material. Against this was the scenario that with time the canisters buried in the bedrock would start leaking.

Still more important, however, was the sense of how these scenarios could be managed. Many Parliament members pointed out that the DiP would not mean that the project would be realised overnight. Instead, the project could still be improved, modified or even cancelled, if better solutions would become available (retrievability was generally considered as an essential requirement for disposal). On the other hand, at the moment there were no other realistic alternatives available for disposal and the rejection of the DiP would mean that no steps were taken at all to protect against the scenario of abandoned waste storage.

Such thinking is an example of the desire to manage the risks, instead of just choosing the risks. As explained by Strydom (2002) in his detailed account of risks in history, the introduction of new stakeholder groups into decision making on actions entailing risks will necessarily mean the end of the paradigm in which the experts assess the risks and the decision-makers then choose the lowest risk. The stakeholder participation means that the cognitive understanding of risks (constructivist risk) means more than the risk numbers. In addition, the experience shows that in such situation the focus is shifted from risk acceptance to risk management, to the question of how to act in a situation in which there are dangers of negative effects.

Strydom's description of changing risk paradigms is clearly visible in the present discussion of high-level nuclear waste disposal. Independent of the opinions of nuclear waste experts, retrievability and possibilities for long-term monitoring are highly valued in public discussion. Both ideas reflect the desire to incorporate some level of manageability in the waste disposal plans, how final they ever are supposed to be.

References

Posiva Oy (1999a), *Application for a decision in principle on the final disposal facility of spent fuel*. Posiva Oy, Helsinki (in Finnish).

Posiva Oy (1999b), *The final disposal facility for spent nuclear fuel – Environmental impact assessment report*. Posiva Oy, Helsinki.

Strydom, P. (2002), Risk, environment and society. Buckingham, Open University Press.

EXPERIENCE OF RISK PERCEPTION FROM OSKARSHAMN MUNICIPALITY

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General background

The Municipality of Oskarshamn is one of two Swedish municipalities currently subject to site investigations for a possible final repository for spent nuclear fuel. The site investigations follow feasibility studies in eight Swedish municipalities. The implementer Swedish Nuclear Fuel and Waste Management Company – SKB has plans to file a license application for a repository in 2008. The application must, among other documentation, include a comprehensive safety analysis report, a detailed site specific systems description and an Environmental Impact Assessment – EIA.

Licensing of a repository in Sweden is subject to three major acts – the Act on Nuclear Activities, the Radiation Protection Act and the Environmental Act. The Swedish Nuclear Inspectorate – SKI prepares the government decision according to the Act on Nuclear Activities. Radiation protection regulations that will have to be followed are set by the Radiation Protection Institute SSI. The Environmental Court prepares the government decision according to the Environmental Act. The municipality has the possibility to veto a repository according to the Environmental Act.

Introduction

Is a final repository safe? That is the key question for the public and the decision makers in Oskarshamn. Before other aspects of a possible final disposal can be discussed there must be a convincing answer to this question.

The main difference between a "conventional" project and a final repository is the comparatively extreme time span during which the spent fuel will have a high potential to threat human health and the environment, should the isolation of the spent fuel not work. The public is well aware and concerned by this fact.

The public is also well aware that the problem must be solved and that it should not be postponed posing a burden to future generations. From several polls there is a clear advice to the experts to continue to develop and test new technology in parallel to the continuous study of geological disposal. In summary the message from the public concerning our spent fuel is – OK go ahead and carry out site investigations for a geological repository but continue to invest in alternative technology where the time span can be shortened.

The consent of the public to a repository will require unbroken trust in the safety case. This does not necessary mean a detailed understanding of performance assessment and all the processes and events that are evaluated and calculated. In a complex safety case like this I would argue that there are probably not even experts that has a detailed and complete understanding of the entire safety case. In the scientific word various facts and quality assurance in a calculation is built up around publishing and peer review.

Where lack of knowledge exist and other uncertainties can not be removed the use of conservative assumptions and scenarios to test the robustness of the system must be used. One can say that if a conclusion is supported by a broad majority of experts it becomes a fact and remains a fact until replaced by another conclusion or theory. The public is well aware of this process and can give examples of the evolution of science in the past.

Siting of a repository is not a decision by experts. It is nor an issue of taking the risk-based decision making from the experts and give it to the public. It is rather the challenge to facilitate risk-based decisions by a sound and balanced participation by all stakeholders in their respective role. From many experts I hear this is not possible, participation requires a certain level of knowledge etc – maybe like a green card in order to play golf – I think such an expert position is a threat to progress in waste management.

In a democratic society final decisions are political and taken by laymen in government and in the case of Sweden also by the laymen in the municipality elected council. The other reality is that the elected decision makers can not take such a decision without public support and the public does not have resources or time to study the detailed safety case. To be provocative the final decision if a repository is safe or not is completely in the hands of laymen.

How then to establish that an acceptable safety case exist with the laymen decision makers?

This is a question that has concerned those of us working with the issue of siting a final repository for many years and I am quite optimistic that there are ways to reach rationale decisions also in a complicated safety case as a repository. There are many aspects of this work and it would take to long to cover them all. In order to trigger this working group discussions I have organised this talk around four key aspects:

- A clear description of what the project is all about and what the alternatives are.
- A well defined decision making process and clearly defined roles of the key actors.
- An open process allowing for participation and influence.
- Facts, values and stretching.

A clear description of what the project is all about and what the alternatives are

Spent nuclear fuel and high level waste is extremely hazardous for hundred thousand years or maybe more. If not handled correctly in the short term and effectively removed from the biosphere in the longer term it poses significant threat to many generations. Temporary solutions in the form a an interim storage may be OK for shorter time periods of say hundred years but for longer term a final solution must be found. The solution that most scientists and experts are suggesting is to finally solve the waste problem by disposing it in a geological formation. This is also what is reflected in the Swedish legislation. This is also what many national programmes initially has aimed for and it has been pointed out as the only solution but strong public opposition has brought especially the siting projects to a halt.

In response to public concerns the original goal – a final disposal – has been re-defined by adding features to comfort the public and decision makers. Phased decision making, long term monitoring, pilot plants, reversibility and retrievability are such additions. From a long term safety perspective none of these additions play any importance e.g. there are hardly points that stem from experts or performance assessment requirements. These are additions that have been introduced for management reasons because they are thought to ease public concern.

From the experience in Oskarshamn none of these additions are "required" by the public as often is referred to in waste management seminars and symposia. From our discussions in Oskarshamn we rather see the opposite required namely to bring a clear message about what waste management is al about, an open discussion about the general options – wait and see, long term monitored surface storage, transmutation, geological disposal etc with the public and the decision makers. These parties can among themselves with expert support work out the arguments and reach conclusions on the preferred option. One conclusion reached in Oskarshamn supported by 80% of the public and 49 out of 50 council members is that we shall continue to work on the geological disposal option by carrying out site investigations in preparation of a licence application. The public is here in pace with the experts – namely development of a geological disposal seems to be the preferred option as of now but the door should also be kept open for other alternatives. I do not think all programmes have this platform.

A well defined decision making process and clearly defined roles of the key actors

In complex decision making the format is as important as the content. Changing rules, parallel discussions about process and content, vague roles of the participants and a feeling of being excluded by the public are ingredients that will stop any nuclear waste project.

A system starting with a clear legislation, a stringent safety standard defined in advance, a clearly defined implementer with authority to propose solutions and sites, a strong regulator with a mandate to follow and review the implementer programme – and stop it if necessary, a local veto or at least a strong local role together with well defined decision making steps are what I would define as necessary ingredients of a sound national nuclear waste programme.

An open process allowing for participation and influence

Reality is that the public does not have much interest in a national R&D programme for how the nuclear waste is to be handled and disposed. The interest will arise when the finger is put on the map and potentially interesting sites are identified. From an expert point of view the programme has probably been running for decades and solutions are seen as mature. For the public a completely new issue is now on the agenda and they see this as the staring point and also see it as their right to question all and any aspect of the proposal. This is frustrating to the experts as they already see many questions as finally solved. Maybe this is the most critical point for any nuclear waste project and where probably the explanation is to be found why so many fail.

At this juncture the experts and laymen must meet, allow time for discussions and be prepared to give and take. If the experts takes on the role that they know all the answers and only takes it as an information problem there is again a large likelihood of failure.

The key is to take the time required for participation and influence. How can the project be set up to allow true participation by the local public and the local decision makers and how can the local expertise be utilised to form a better project? The answers to these questions are key to progress in any siting programme. For those experts and managers that do not think there is anything to learn from the public and local decision makers and that participation is only a burden I can foresee large problems and distrust.

Facts, values and stretching

With this fourth point I will try to address how to formulate the answer to the question from the public – is it safe?

As implied by the questions given to WG 1 in the invitation to this workshop answers are sought on questions on to what level should the safety case be presented to the public and decision makers. I am sorry to say that there are no answers to these questions. My answer is rather formulated as a recommendation on how to work – go out there and engage and you can be sure that the decision makers and the public will guide you to what level they are interested.

Important is to set up various forums where expert and laymen can meet. From our experience it is of crucial importance that the experts from the regulator participate in these forums.

Safety analysis does no only include facts but also contain value judgements on several levels.

My experience from Oskarshamn tells me that the answer to the question – is it safe? – contains two main components namely how the soundness of the system itself is perceived and secondly can the experts be trusted. The experts can roughly put in three groups – those who are developing the technical details (for the implementer) those who are critical and maybe also linked to the environmental groups and those working for the regulator who review and approve. The role of the regulator is often underestimated. A strong, competent regulator with the legal tools and resources to participate is based on our experience in Oskarshamn crucial if we are to reach solid and respected decisions.

For the critical experts from e.g. the environmental groups we must find forums where they can ask their questions and where these questions are addressed by experts from both the implementer and the regulator. The RISCOM project has developed a model how this can be handled. The concept of stretching is one important aspect of establishing authenticity by the experts and thus in the extension in their recommendations. To establish a demanding environment for the experts where the issues can be thoroughly stretched is one important ingredient if decision makers and the public will trust the safety case or not.

CONCEPTS OF UNCERTAINTY CLASSIFICATION AND NEW METHODS OF RISK ASSESSMENT FOR THE DISPOSAL OF RADIOACTIVE WASTE

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Introduction

Risk and uncertainty assessments are the topics of the Working Group discussions. "*How can tools and experiences from outside the nuclear waste field be used in the characterisation of uncertainties*" was one of the questions sent out to the participants. The authors of this paper are working for several years on the concepts of uncertainties and risks in geologic investigations. They came to the conclusion that the application of up-to-date mathematical methods is crucial for the handling of uncertainties and risk in geology in general, and particularly in the field of nuclear waste disposal (Bárdossy and Fodor, 2003). The results of their investigations and examples of their test calculations are reviewed in this paper, considered as an answer to the above question.

Definition of the uncertainties and their classification

Uncertainty is in our opinion a general term expressing a lack of certainty and precision in describing an object, a feature or a process. Of course, this is a first approximation. The term has been defined more precisely by mathematicians:

> *"Uncertainty implies that in a certain situation a person does not dispose about information which quantitatively is appropriate to describe, prescribe and predict deterministically and numerically a system"* (Zimmermann, 2000).

According to Dubois and Prade (2000) and Zimmermann (2000) the following types of uncertainties can be distinguished in mathematical respect:

1. *Imprecision or inaccuracy,* expressing the deviation of measurements from a true value. The term *error* represents the numerical difference of the measurement result from the true value. It is a well known axiom that all measurements inevitably result in some – even very small – error. The term *bias* is used in the case of consistent under- or over-estimation of the true value.
2. *Vagueness or ambiguity* expresses the uncertainty of non-statistical or non-measurable properties or objects. In these cases the measurements are replaced by observations or linguistic descriptions ("semantic ambiguity").
3. *Incompleteness* is a type of uncertainty when the amount of information or knowledge is insufficient to perform an adequate evaluation of the given problem.
4. *Conflicting evidence* when information is available pointing to a certain evidence, but there might be some further information, contradicting and pointing to another evidence.

5. *Belief* when all available information is subjective. In this context one must always distinguish *objective information* (measurements, descriptions, observations) from *subjective information.* The well known term *expert's opinion* belongs to latter group.

The above classification is valid for geological problems as well. However the complexity of most geological investigations require a more detailed classification. Recently such a classification has been elaborated by us, based on the *sources of uncertainty* (Bárdossy and Fodor, 2003, in press).

Only the main groups are listed here:

1) Uncertainties due to natural variability.

2) Uncertainties due to human imperfections and incomplete knowledge.
   2.1. In the phase of preparing the input data.
   2.2. In the phase of evaluation and modelling.

It is obvious that the different types of uncertainty need different methods of representation and mathematical evaluation. Natural variability is a property of Nature, existing independently of us. It can be studied, quantified and described, but it cannot be diminished. On the other hand, the uncertainties due to human shortcomings can be diminished to a certain extent. The fundamental difference of these two groups is often neglected even at recent geologic investigations. The above classification is of generic character. It must be completed by site specific and target specific types of uncertainties and this is the case of the disposal of the radioactive waste as well. The following types of uncertainties have been distinguished in the safety assessments performed by us, taking into account the internationally distinguished FEPs (features, events, processes):

1. *Uncertainties due to natural variability*. Structured and unstructured variability can be distinguished. Structured variability can be quantified and mathematically described by *trend analysis*. On the other hand, unstructured variability may occur unexpectedly, its spatial position and magnitude cannot be exactly predicted. The higher the proportion of the unstructured locations (spatial points), the higher is the uncertainty of the given site. Not only spatial, but also time dependent variables are among the FEPs, producing additional uncertainty.

2. *Uncertainties due to human shortcomings*.
   2.1. *In the phase of preparing the input data*
      2.1.1. Uncertainties of the concepts and requirements of the site selection
      2.1.2. Uncertain knowledge about the activity concentration of the waste to be stored in the given repository
      2.1.3. Uncertainties of the field observations at the future site
      2.1.4. Uncertainties due to incomplete sampling (outcrops, treches, boreholes, galleries)
      2.1.5. Uncertainties due to incomplete application of geophysical and geotechnical methods
      2.1.6. Incomplete selection of the types of laboratory measurements
      2.1.7. Analytical errors of the laboratory measurements

   2.2. *In the phase of evaluation and modeling*
      2.2.1. Conceptual and model uncertainties
      2.2.2. Uncertainties in the selection of possible future scenarios (base case, and additional cases)
      2.2.3. Uncertainties of mathematical modelling
      2.2.4. Uncertainties due to the incorrect application of mathematical methods

2.2.5. Uncertainties due to error propagation and the establishment of the final dose rates
2.2.6. Technical and other non-geological uncertainties

So far all safety assessments have been executed either by deterministic or by probabilistic methods. They are mathematically correct, but they have limitations, to be outlined in the next section.

Advantages and limitations of the deterministic and probabilistic methods

In the case of the *deterministic methods* the dependent variable is completely controlled by one or several independent variables. The input data have one (single) value, without any reference to their errors or uncertainties. Thus they are considered as true, crisp values. The final results are point-estimates, corresponding to the *best estimate concept.* This approach is straightforward, but do not take into account the inevitably existing errors and uncertainties. In our opinion, all input data of the safety assessments, seemingly precise (true), harbour some degree of uncertainty. Consequently, deterministic safety assessments can furnish unbiased results only if all FEPs are precisely known. To eliminate this shortcoming, single parameter *sensitivity analyses* are performed, one by one for the main FEPs. This procedure produces mathematically correct results, but again in the form of point estimates. For this reason the deterministic approaches are considered by us to be less suitable for the safety assessments.

The method called *worst case analysis* is an approach that acknowledges the presence of uncertainty in the system without modelling it explicitly. It takes into account the upper, or lower bounds of the distribution, attempting that no larger (or smaller) values will occur in the system. This approach has been applied in several safety assessments by designating “realistic”, “pessimistic” or “conservative” values. The realistic values correspond to the results of the “best estimate” and the latter expressions to the worst case. The method of their calculation is generally not presented in the safety assessment. The application of multiplication factors of 2, 5, 7, 10 and even of 100 to arrive to the “conservative” value lacks any geological justification and should be avoided. Experiences in other fields of research showed that many worst case analyses produced hyper-conservative results.

The well known *probabilistic methods* found broad application in safety assessments of several countries. These methods also operate with single (crisp) numbers as input data, but they express the uncertainty by probability distributions, and confidence intervals at chosen levels of confidence. In our opinion, the probabilistic methods have the following limitations for their application to safety assessments:

a) The uncertainties of several input data, listed in the foregoing section, cannot be taken into account

b) The basic axioms of the probability theory deal only with disjunct, mutually exclusive subsets. However in geology, including the sites of future repositories of radioactive waste, disjunct subsets are very rare. Transitions are much more frequent. At many sites there are more transitional zones than pure geological objects. In such cases artificial, sharp boundaries must be designated when applying stochastic methods. This is a gross distortion of the natural reality leading to biased final results.

c) Several statistical procedures require *repeated experiments (trials),* which implies that the variables must be random. Note that drilling and sampling of a borehole is in statistical sense also an experiment. Let us take a set of boreholes, drilled in a regular grid. The requirement of repeated experiments would mean repeated drilling of the grid after shifting and rotating the original grid locations. Obviously, such a procedure is unfeasible, even nonsensical. For this reason several statistics cannot be calculated in a mathematically correct way. Furthermore, uncertain propositions cannot be defined in terms of repeatable experiments.

d) Subjective probabilities, based on expert's knowledge cannot be correctly included into the classical statistical calculations.

e) The Monte Carlo simulation, one of the most frequently applied tool of numerical calculations of stochastic methods, generally works with the assumption of *independence* between the random parameters. However, this very rarely occurs in geological systems, particularly for the FEPs of the safety assessments. Interdependence of the variables may lead to significant errors in the final results. Finally, Monte Carlo analysis is inappropriate for semi-quantitative and qualitative input data and for non-statistical uncertainty.

For the above reasons probabilistic safety assessments might be more or less biased. As all the input data are crisp numbers, only the natural variability can be taken into account by the probabilistic methods. The errors due to human shortcoming, often of significant amount, cannot be correctly evaluated by the traditional methods. This is the reason for the application of the *uncertainty oriented* mathematical methods to be reviewed in the next section.

Review of the uncertainty oriented mathematical methods and their advantages

During the last decades new mathematical methods have been developed that are capable to handle the above listed limitations and shortcomings of the traditional methods. The first attempts were made with the aim to include subjective information and prior probabilities into the probability calculations. Note that probability is an abstract mathematical concept that may be defined in two different ways: *Frequents probability* is defined as a limiting frequency of a particular outcome in a large number of identical experiments. *Bayesian probability* can be defined as the degree of belief in a particular outcome of a single experiment. Thus it depends not only on the phenomenon itself, but also on the prior state of knowledge and the beliefs (experiences) of the observer. Bayesian probability changes with time, as our knowledge increases about the given phenomenon. This approach is called "Bayesian" because its proponents use the well known *Bayes theorem* of conditional probabilities for the calculation of subjective probabilities. In this context a *prior probability* is the probability of an event prior to updating, that is using new information. On the other hand, *posterior probability* is the updated probability of the event, based on all new information. According to our experiences the concept of Bayesian probability is suitable for the safety assessment of radioactive waste disposal, particularly to take into account valuable subjective information.

The *Dempster-Shafer theory of evidence* is another approach to use probabilities in subjective judgements. The theory is based on two ideas: obtaining degrees of belief for one question from subjective probabilities and the Dempster's combination rule for aggregating degrees of belief when they are based on multiple sources of evidence. The theory and its application are discussed in detail in the book of Bárdossy and Fodor (2003 in press).

One of the main tools of statistical calculations, including safety assessments is the *Monte Carlo simulation.* The method requires the knowledge of the probability distribution of each variable, their mean and variance. However this is in many cases not known. The bias due to the assumption of independence of the variables has been already mentioned in the foregoing section. Ferson (1994, 1996) pointed out that the results of Monte Carlo simulation often under-estimate the probability of high exposures and the high-consequence effects of such exposures. He suggested the application of "*dispersive Monte Carlo simulation*" under the assumption of linear correlation among the variables, and *„dependency bounds analysis”* when no assumptions are made about the type of correlation. Another solution is the application of the *Latin hypercube sampling*, assuring a more complete sampling of the sample space.

Let us stress that the frequently used term of “*uncertainty analysis”* was applied so far only to deterministic and probabilistic safety assessments, as the uncertainties and errors of crisp input data cannot be evaluated by these approaches. The main advantage of the uncertainty oriented methods is that they are able to describe the uncertainties by different *uncertain numbers.* The simplest of these methods is the *interval analysis.* It replaces the crisp input numbers by uncertainty intervals. It is assumed that the true value is somewhere within the interval. Interval analysis lacks gradations, but it guarantees that the true value will always remain within the uncertainty interval. During the calculations the intervals become wider and the final results are mostly hyper-conservative.

The *possibility theory,* a generalisation of the interval analysis, provides a suitable model for the quantification of uncertainty by means of the possibility of an event (Zadeh, 1978). The theory acknowledges that several types of data cannot be handled by probability distributions. Instead it uses *membership functions* to represent non-statistical uncertainty. The membership value of a number, varying between zero and one, expresses the plausibility of occurrence of that number. The related *fuzzy set theory* operates with fuzzy sets, that is, sets without clear boundaries and well defined characteristics. Fuzzy numbers represent estimates of uncertainty at different levels of possibility. Fuzzy numbers are by definition unimodal and they must reach at least in one point the possibility level one, that is the full possibility. The smallest and the largest possible values of the given variable represent the lower and the upper bounds of the fuzzy number. All arithmetic calculations can be carried out with fuzzy numbers. One of their great advantages is that they do not require the knowledge of correlations among the variables and the type of their probability distribution. They are not influenced by the limitations of the “closed systems”. Fuzzy numbers can be reconverted into crisp numbers. This calculation is called *defuzzification.* But the main advantage is that prior geological experience can be incorporated into the construction of the fuzzy numbers. The frequent transitions of geological FEPs, mentioned in the foregoing sections can be also represented by fuzzy numbers.

The *probability bounds theory* is a combination of the probability theory with interval analysis. It expresses the uncertainty of the input data by two cumulative probability distributions. The area between the two curves represents the extent of uncertainty of the given variable. The advantage of this method is that it can apply different probability distributions, but the method works also without making any prior assumptions. The probability bounds get narrower with more empirical information about the given geological object (site). The calculations with this method are more complicated than with the foregoing methods. Nevertheless, it can be highly efficient for safety assessments, when prior information is abundant.

The method of *hybrid arithmetic* (Ferson and Ginzburg, 1996) combine probability distributions with uncertainty intervals, fuzzy numbers and probability bounds. Its greatest advantage is its ability to combine different uncertain input data. Guyonnet *et al.* (2003) suggested another hybrid method combining Monte Carlo simulation with fuzzy numbers.

In our opinion, no single uncertainty theory can be claimed to be the best for all types of uncertainty and all geological objects and situations. This is particularly valid for the case of safety assessments. According to our experiences the fuzzy set theory seems to fit well in most cases, because of its relative simplicity, transparency and its ability for the inclusion of prior geological information. But it can be completed, according to the site specific conditions, by the other methods outlined above.

Risk analysis and its application to radioactive waste disposal

Risk is a common term in science, economy and industry. The notion of risk has been defined in many different ways leading to much confusion. We apply therefore the definition of the Society of Risk Analysis: “Risk is the potential for the realisation of unwanted consequences of a decision or an action”. Risk analysis is of particular importance for the safety assessment of radioactive waste disposal. To our knowledge, only deterministic and probabilistic risk analyses have been performed so far in this field. However, the evaluation of the related uncertainties is of crucial importance for the reliability of the risk assessments. This problem has been discussed recently in detail by Helton (2003) based on probabilistic methodologies. These methods are mathematically correct, but in our opinion not optimal. This is why we suggest the application of the above listed uncertainty oriented theories.

A common feature of the traditional methodologies is the assumption of linearity and independence between the input parameters. Unfortunately, this is almost never valid for the sites of radioactive waste disposal. As already mentioned above, the application of the traditional Monte Carlo simulation often leads to the under-estimation of the “tail-probabilities”, that is of risks of low probability, but of severe consequences. The methods of fuzzy arithmetic and fuzzy logic have been applied to risk analysis first in the nineties, for industrial and ecologic problems. A joint stochastic and fuzzy approach for risk analysis has been published by Ru and Eloff (1996). A very attractive feature of this approach is that the output for each identified risk-factor is provided on the same scale, so that they can be directly compared. The hybrid approach of Guyonnet *et al*., (2003) mentioned above is able to take into account both crisp and uncertain data for the risk analysis. Thus it allows the quantitative assessment of the *reliability of the risk statements* of the given safety assessment.

It is of key importance that risk analyses should not be considered as a black-box system which magically provides answers that need to be fully trusted. The user should be able to follow each step of the risk analysis, checking and if necessary correcting it. This transparency is fully provided by the fuzzy methods, suggested by us. The application of this methodology is illustrated on two examples performed by us in Hungary.

Examples of safety assessments performed by the methodology of the fuzzy set theory

The first example is the acting repository of low and medium radioactive waste of **Püspökszilágy,** situated 32 km to the northeast of Budapest. Its construction has been finished in 1976. It is a surface repository located on the flat top of a low hill. The full capacity of the repository is 5 120 m^3. Two safety assessments have been performed in the year 2000, one by the AEA Technology (United Kingdom) and the other by ETV-ERŐTERV (Budapest), both applying deterministic methodology. The test calculations of the authors were carried out in 2002, based on the fuzzy set theory.

The hill is elongated in NW/SW direction and is flanked by two creeks, being the hydrogeological base of the groundwater system. The upper part of the hill consists of Quaternary loess of 5 to 30 m thickness. It is underlain by marine clay of upper Oligocene age, of 400 to 500 m thickness.

5 930 waste packages arrived to the repository until 31 December 2001. They have been disposed in four types of disposal units: most of the waste in large concrete vaults in plastic bags or in metallic drums. A smaller amount of waste was disposed in small concrete vaults in metallic drums. A further part in stainless steel wells of 40 to 100 and 200 mm diameter for sealed radiation sources. The repository is covered by a 60 cm thick concrete slab and a clay layer of 2 m thickness. The following

main components of the waste have been involved into the calculations: ^{3}H, ^{90}Sr, ^{137}Cs, ^{63}Ni ^{14}C and ^{239}Pu (the letter present in very small amount).

The following normal *evolution scenario* was established: The repository will be closed on 1 January 2006. It is estimated by the experts that the concrete slab cover will collapse gradually after 500 years. This allows the infiltration of meteoric water and the leaching of the radioisotopes will start. The solutions will migrate downward to reach the groundwater level, situated about 20 m below the bottom of the repository. Hydrogeologic boreholes established that the groundwater slowly migrates laterally, mainly in south-eastern direction, to reach the Szilágyi creek at a distance of 1 000 to 1 100 m. A smaller portion migrates south-westward to reach the Némedi creek at a distance of 400 to 500 m. The dissolved radionuclides will reach the biosphere along these two creeks.

First the activity of the six selected radioisotopes was established for the reference date of 1 January 2006, fuzzy numbers expressing their uncertainty. For the decay of the waste packages estimates were made by experts, based on their own experiments and on international experiences. Fuzzy numbers were constructed by us for all types of waste packages. Below the minimum value of the fuzzy number no escape of radioisotopes is estimated. On the other hand, when reaching the full membership, no more protection is estimated for the given type of package. Further fuzzy numbers were constructed for the decay of the of the disposal units.

In the next step activity concentrations were calculated by us for the leached radio-isotopes, just below the bottom of the repository. The results were listed in 58 time levels, ranging from the first to 100 000 years, separately for the six studied radioisotopes. The uncertainties are expressed again by fuzzy numbers. The estimation of the time interval of downward migration includes a large amount of uncertainty, that could be adequately expressed by a trapezoidal fuzzy number. According to the experts, no significant dilution of the solutions occurred during this downward migration. The activity concentrations (Bq/m^3) were calculated again for the 58 time levels at the groundwater level, below the repository.

For the time interval of the lateral groundwater migration further fuzzy numbers were constructed, the minimum time being 150 and the maximum 500 years for the Szilágyi creek. Hydrogeologic investigations demonstrated that the migration occurs almost parallel, no migration fans are formed. Laboratory measurements showed that 20 to 80 % of the dissolved radioisotopes are absorbed by the sediments during the lateral migration. The high uncertainty of these measurements can be taken into account by further fuzzy numbers. Finally the activity concentrations for the 58 time levels were calculated at the arrival of the solutions at the Szilágyi creek, that is the biosphere. The results were presented in tables and in time dependent diagrams. As a final step, the sum of the activity concentrations and dose rates were calculated, the uncertainty of the estimate expressed by fuzzy numbers. The results are in good agreement with a recently finished probabilistic safety assessment, the payoff being the sound and mathematically correct quantification of the estimation uncertainties.

A second safety assessment performed by fuzzy numbers has been finished recently for the underground repository to be constructed at **Bátaapáti,** in southern Hungary. The assessment is based on the recently finished geological and geophysical surface investigations. The repository will host waste of low and medium activity of the Paks nuclear power plant. The host rock is Carboniferous granite, fractured by Hercynian and Alpine tectonic movements. A special hydrogeologic model was constructed to take into account this particular feature. In 2000 a deterministic "preliminary" safety assessment was carried out by ETV-ERŐTERV (Budapest). For our safety assessment the construction of the fuzzy numbers occurred in the same way as in the foregoing case. Furthermore, a detailed mathematical model was applied, based on the model suggested by Hedin (2002). Instead of crisp numbers fuzzy numbers have been inserted into Hedin's equations. The results obtained are in good accordance with those of the deterministic calculations. The main advantage is the transparency of the calculation and the quantification of the uncertainties and of the overall reliability of the safety assessment.

Conclusions

Both theoretical evidences and the results of our test calculations demonstrate that the application of the uncertainty oriented mathematical methods for safety assessments is justified and useful. Their main benefit is the mathematically correct, sound quantification of the uncertainty of the given safety statement. The new methods are considered by us as complements to the existing deterministic and probabilistic methods.

The authors of the paper suggest to perform test calculations parallel with the traditional probabilistic safety assessments, based on the same set of input data. International cooperation would facilitate to start such calculations.

The mathematical correctness of the calculations is crucial for the success of the calculations. It is suggested therefore to involve skilled mathematicians into each test calculation.

Selected references

Bárdossy G., J. Fodor (2001), New possibilities for the evaluation of uncertainties in safety assessment of radioactive waste disposal – Acta Geologica Hungarica, 44, pp. 363-380.

Bárdossy G., J. Fodor (2003), Evaluation of Uncertainties and Risks in Geology – Springer Verlag. Heidelberg, New York, 230 p. (in press).

Dubois D., H. Prade (2000), Fundamentals of Fuzzy Sets – Kluver Academic Publishers, Boston, London, Dordrecht, 647 p.

Ferson, S. (1994), Naive Monte Carlo methods yield dangerous underestimates of tail probabilities. Proc. High Consequence Operations Safety Symposium, (SANDIA Report SAN94-2364, pp. 507-514.

Ferson, S. (1996), What Monte Carlo methods cannot do – Human and Ecological Risk Assessment, 2, pp. 990-1007.

Ferson, S., L.R. Ginzburg (1996), Different methods are needed to propagate ignorance and variability – Reliability Engineering and System Safety, 54, pp. 133-144.

Guyonnet, D., B. Bourgine, D. Dubois, H. Fargier, B. Come, J-P. Chiles (2003), Hybrid approach for addressing uncertainty in risk assessments – Journal Environ. Eng. Assos, 129, pp. 68-78.

Hedin, A. (2002), Integrated analytic radionuclide transport model for a spent nuclear fuel repository in saturated fractured rock – Nuclear Technology, 138, pp. 179-205.

Helton, J.C. (2003), Mathematical and numerical approaches in performance assessment for radioactive waste disposal: dealing with uncertainty – In: "Modelling Radioactivity in the Environment", E.M. Scott (Ed.), Elsevier Science Ltd, Amsterdam, pp. 353-390.

Zadeh, L.A. (1978), Fuzzy sets as a basis for a theory of possibility – Fuzzy Sets and Systems, 1, pp. 3-28.

Zimmermann, H.-J. (2000), An application oriented view of modelling uncertainty – European Journal of Operational Research, 122, pp. 190-198.

WORKING GROUP 2

REGULATORY REQUIREMENTS AND REVIEW OF UNCERTAINTY AND RISK IN SAFETY CASES

SSI's REGULATIONS IN CONNECTION WITH POST-CLOSURE RADIOACTIVE WASTE DISPOSAL

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Background

In the Swedish Nuclear Activities Act and the Radiation Protection Act, the waste producer has the full responsibility for i) siting, construction and operation, ii) research and development and iii) financing in connection with disposal of all waste from the nuclear power programme. The Swedish Radiation Protection Authority, SSI, and the Swedish Nuclear Power Inspectorate, SKI, ensure compliance with safety requirements through their programme of regulations and license conditions, supervision, review activities directed towards the operator, the SKB's, programme and their independent research.

The authorities' role in the on-going siting process for a high-level waste disposal facility is to ensure that the siting process is consistent with the requirements in the Swedish Environmental Code regarding the environmental assessment process, and that SKB takes into account the authorities' view in the implementation of their programme for each step. In this process the authorities must strike a balance between their involvement and their independence, in order to be able to carry out a fully independent review of SKB's coming license application.

For the involved municipalities the Swedish Stepwise implementation of the siting process with regular review gives a possibility for the authorities to respond to views and questions from municipalities, organisations and the public.

SSI's regulatory activities

SSI's regulations SSI FS 98:1

The Swedish Radiation Protection Institute's Regulations concerning "the protection of human health and the environment in connection with the final management of spent nuclear fuel or nuclear waste" was promulgated September 28, 1998. The regulations are deliberately and carefully worded in a general style, to account for early steps of repository development. The Swedish Environmental Code requires alternatives solutions to be presented for the proposed way of reaching the goal, and the SSI's regulation cover all such solutions, including such alternatives as very deep boreholes and partitioning and transmutation. The regulations cover both high- and medium level repositories, and thus includes the repository SFR for Intermediate level waste from reactor operation, near Forsmark nuclear power plant. The regulations do not cover landfills.

In its general form, the regulation addresses a large number of issues, such as:

- consequences outside Sweden's borders relating to national equity;

- optimisation and best available technique;
- environmental protection, i.e. protection of non-human species;
- protection of human health, using ICRP's consequence estimates, and a yearly maximum risk level of 10^{-6};
- intrusion and access issues with emphasis put on the undisturbed repository's safety; and
- two time periods with separate requirements. The periods are i) the first thousand years, and ii) the period after the first thousand years following repository closure.

The regulations defines a standard, but its condensed structure does not give guidance as to how the different requirements are to be understood and met in detail, such as is needed in a compliance demonstration.

In connection with the promulgation, SSI published comments and background material to the regulations, published in English in SSI Report 2000:18. These were mainly written to assist SSI's board in their decision to promulgate the regulations, and to explain the regulations to a broader audience. They explain some of the concepts in more detail than the regulations, and they also give justification for some of the decisions behind the regulations.

Experiences accumulated in the time since the promulgation of the regulations, and the progress in SKB's programme implementation has prompted SSI to publicise its assistance and advice in the form of a formal guidance document related to the regulations. The experiences mainly come from a dialogue with both the public, especially from the involved municipalities, and from SKB. These, and other stakeholder groups, have formulated questions regarding the regulations in statements, in part solicited by SSI in a series of meetings directed towards the regulations, regarding all aspects of the regulations but particularly about the concept of health risk limitation.

The scope of the guidance is limited to geologic disposal, which allows for a much more focused treatment, relevant for the current radioactive waste programme.

SSI's work on the guidance document takes up a number of issues, such as:

- Optimisation and best available technique. Today, ICRP proposes a broader definition of optimisation than before and this need to be reflected in the guidance. Best available technique, BAT, can sometimes be used in parallel with optimisation, but in some cases, optimisation may not be possible even if all exposure patterns are known, i.e. for protection of the natural environment.
- to what extent can ICRP's interpretation from publication 81, that siting issues play a role in optimisation, be expressed in regulatory documents?
- Human intrusion. Human intrusion is an illusive concept in more ways than one. The probability of its occurrence and the form of the intrusion are examples that may lead to endless speculation, unless precautions are taken. This is already recognised in the regulations to some degree, but there are still a number of questions, which may need guidance. Some examples are:
  - Where should the dividing line between intrusion and the undisturbed case be drawn for shallow depth repositories (tens of meters)? Is it intrusion to drill a well near, but not through, the repository?

- What is a reasonable effort in proving the mitigating or self-healing properties of the chosen repository concept?
- Should the value of post-closure archives in promoting a passive institutional control be expressed in the guidance?

- Definition of end-points. Issues related to the person(s) receiving the highest dose. Both USEPA and USNRC use a hypothetical test person, but ICRP has two concepts, the test person which is mentioned in publication 43 and the critical group from publication 81.
- Dilution. Is it acceptable that the main contribution to compliance is dilution in the Baltic Sea (or other water bodies) for a repository that would otherwise not be accepted?
- Technical issues, such as treatment of geosphere-biosphere interface. In radionuclide transport from the rock to the biosphere there are a number of potential accumulation processes must be taken into account.

SSI's work with the guidance document is planned to be finalised in 2004, and it includes both national and international consultation.

THE MANAGEMENT OF UNCERTAINTIES IN THE FRENCH REGULATION ON DEEP DISPOSAL: THE DEVELOPMENT OF A NON-RISK BASED APPROACH

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The development of a safety case for disposal of high level and medium level long-lived waste in a geological formation has to handle two main difficulties:

- uncertainties associated to natural systems;
- uncertainties associated to the consideration of long time scales.

Licensing of the different steps leading to geological disposal implies thus that a sufficient level of confidence in the safety case will be obtained, at each step, among the different stakeholders.

The confidence in the safety case relies on the whole set of arguments of different natures which complement each other and build up the file. This means that, to be defensible, the safety case should be organised in such a way that it can be reviewed and scrutinised in a structured manner. This also means that individual elements of the safety case will have to be considered separately even if all elements should fit well in the integrated safety case. This segregation implies some inherent decoupling of parts of the system, of its evolution over time and of the events that may impact on it. This decoupling will thus introduce inherent uncertainties that risk or non-risk based approaches have to deal with since both approaches have to introduce transparency in the analysis. In the non-risk based or deterministic approach this segregation is pushed further in order to put into perspective the different elements of appreciation that allow to judge the safety case as a whole.

The French regulation on deep disposal presented in the basic safety rule RFS III.3.f, issued in 1991, takes these points into consideration to set the basis for the safety case in the framework of a deterministic approach. This basic safety rule is currently being revised in order to clarify some concepts and to take account evolution of ideas at the national and international level. However the basic rationale behind the safety assessment methodology will remain the same.

The approach presented in RFS III.2.f implies that at different levels in the safety case the emphasis is given on the transparency and traceability of the assessment and the arguments being developed rather than on the performance value in terms of dose or risk which is only one element of judgement among the whole set of arguments that are being reviewed in order to assess a safety case.

The present document will thus stress the basic choices made in developing RFS III.2.f that allow to put forward the different arguments of safety in order to build up a defensible safety case which may be thoroughly reviewed.

These elements may be identified as follows:

- complementary lines of evidence;
- focus on limited number of representative situations;
- multi-attribute judgement of radiological impact;
- thorough management of uncertainties.

These different aspects will be developed and compared with the situation when a risk-based approach is used.

The different components of the safety assessment

The basic philosophy of RFS III.2.f is that compliance with radiation protection objectives is only one element of the safety case. As indicated in the safety rule, the safety assessment should address the following elements:

- assess the adequacy of the components of the repository justifying their suitability by qualitative and quantitative arguments including traceability, quality management and qualification procedures;
- check the robustness of the repository by considering the different kinds of events and processes that may affect it and prove that there are adequate lines of defence in front of these events (in a qualitative and quantitative way);
- assess the future evolution of the repository and verify that radiation protection objectives are met.

The safety assessment, as described in the basic safety rule RFS III.2.f, comprises thus a set of qualitative and quantitative arguments that build up confidence in the safety of the disposal system.

This approach, presented in the safety rule, shows an evolution from the original trend of restricting the judgement on the safety case on the assessment of a global risk. Emphasis is given on the development of multiple lines of evidence which complement each other. This approach has been adopted at the international level and constitutes now the basis for the safety case recommended by the OECD/NEA. Therefore the risk approach, when it is used, concerns now only one of the different components of the safety case, the quantitative analysis which should assess compliance with radiation protection objectives.

Scenario analysis

In order to assess the future evolution of the repository the basic safety rule RFS III.2.f recommends to use a transparent method by considering a limited number of situations representative of the different families of events or sequence of events that may affect the repository.

The situations are classified into likely situations which take into account highly probable events and processes and for which consequences are the most important bases of judgement, unlikely situations where consequences as well as frequencies are considered and very unlikely situations which may have high consequences and for which the judgement is based mainly on the justification of the low frequency of the situation. Other situations associated with future actions are treated separately with stylised assumptions.

The RFS III.2.f recommends to analyse each type of situation separately and to draw an overall judgement on individual compliance for each situation.

In the case of a global probabilistic risk approach each situation corresponds to an individual sampling of all possible events and values of parameters in the time period of interest. Hundreds of situations or realisations are thus derived each leading to a different impact from the repository. The complete distribution of possible impacts allows to calculate a risk.

This global probabilistic risk approach is now seldom used even in the framework of a risk based assessment and the consideration of a limited number of representative situations is often preferred each leading to the estimation of an individual dose or risk. Judgement should therefore be used to put the emphasis on consequences associated to certain types of situations rather than others.

The restriction of the analysis to a limited set of representative scenarios clearly improves the transparency of the assessment and helps structuring the review of the safety case. It introduces however some uncertainties by not taking into account the complete set of combined events which are considered when using the full probabilistic approach described above. This implies that both for the risk approach and the deterministic approach a trade-off should be made between transparency and completeness.

Compliance with radiation protection objectives

In the RFS III.2.f, the radiation protection objectives for assessing compliance depend on the types of situations:

- For very unlikely situations the emphasis is given to the probability of the corresponding events and illustrations of the consequences.
- For likely situations a dose or several dose calculations are performed. The objective is to judge what are the margins between the result and the objective but more importantly the sensitive elements that may affect these margins. The emphasis is given to these sensitive elements and the safety case indicates all the efforts that have been put forward by conceptual design, R&D and site investigation in order to reduce uncertainties associated with this sensitive elements.
- For unlikely situations all arguments are considered and weighted to judge the acceptability of consequences. The comparison of the product of the consequence by the probability to the risk constraint is just one line of argument.

These objectives show that, even for a non-risk approach, frequencies of occurrence and probabilities are considered for judging the case. However, in a deterministic approach, and in contrast with the risk approach, consequences, probabilities and other elements of judgement are considered individually in the framework of a structured and transparent process. This is an important feature because each of these elements is not obtained with the same level of confidence and it should be given the appropriate weight in the global judgement.

Management of uncertainties

Uncertainties are the main sources of lack of confidence in the development of the safety case. The RFS III.2.f stresses that these uncertainties should be adequately addressed in an open manner and that they should be the basis for going from one licensing step to the next by improving site characterisation, experiments and design studies.

The different sources of uncertainties should be assessed: parameter uncertainties, uncertainties associated with simplification of modelling, conceptual model uncertainties, uncertainties associated with poor understanding of physical processes, uncertainties associated with unpredicted events or human behaviour. It is clear that only part of these uncertainties will be addressed with a probabilistic approach. Therefore the derived risk may not take into account all sources of uncertainties. In any case uncertainties should be thoroughly discussed in the safety case stressing the means which have been used to identify and reduce them. Application of basic safety principles such as demonstrability and robustness of the repository system will increase confidence and reduce overall uncertainty in long term behaviour.

As for quantifiable uncertainties, their influence on the radiological impact should be addressed. In a probabilistic approach, with a dose or risk criterion, this may be done using probability distribution functions and statistical sampling techniques. In a deterministic approach this is usually done by choosing, for individual parameters, best estimate and bounding values. The difficult question is the choice of the range of values to be retained or the choice of the distribution function. Important aspects in the process are thus the elements of judgement that have been used to make the above choices and how they have been traced. In any case, using a performing method for sampling values of parameters on their probability distribution functions and calculating a confidence bound or a risk do not resolve all uncertainty issues for a specific safety case.

Conclusions

The safety case of a HLW repository in a geological formation should satisfy two requirements. It should take into account all the informations about the components of the repository system and their evolution over time in an adequate manner in the objective to manage uncertainties in a uniform, systematic and logical framework. It should as well be transparent for the different stakeholders meaning that they should be able to appreciate the weight given to the different assumptions which have been used. The French basic safety rule RFS III.2.f, now under revision, emphasises the importance of both objectives for the safety case. It stresses the importance of using multiple lines of evidence, complementary qualitative and quantitative arguments and more important to develop a transparent and structured safety case that can be easily reviewed. The approach described in the basic safety rule does not advice to use a risk criterion and is thus considered as a deterministic approach. Nevertheless it takes into account probabilities of situations as one element of judgement and is open to treatment of uncertainties with probabilistic techniques which may be compatible with compliance associated to a dose criteria.

ESTIMATES OF POST-CLOSURE RISK IN REGULATORY DECISION MAKING: ENVIRONMENT AGENCY ISSUES AND OPTIONS

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Introduction

The Environment Agency of England and Wales (the Agency) is responsible for the authorisation of radioactive waste disposal under the Radioactive Substances Act 1993.

British Nuclear Fuels plc (BNFL) is currently authorised to dispose of solid low-level radioactive waste at a disposal facility near the village of Drigg on the Cumbrian coast, in north-west England. In accordance with Government Policy, the Agency periodically reviews authorisations for the disposal of radioactive waste.

The Agency intends to commence its next review of the Drigg authorisation in 2003/4. To inform its decision making, the Agency required BNFL to submit new safety cases for the Drigg disposal facility in September 2002. These have been received from BNFL and made publicly available (via national public registers):

- The Operational Environmental Safety Case [1] considers the impacts of the facility on the environment and the public in the period whilst the site remains operational and under institutional control, which BNFL estimates might be 2150.
- The Post-Closure Safety Case [2] considers the long-term environmental impacts of the facility after 2150 and includes a Post-Closure Radiological Safety Assessment, which is a risk assessment.

This paper deals with estimates of post-closure risk, it specifically excludes the operational phase and regulatory controls thereon. The paper summarises work undertaken by the Agency to consider potential regulatory actions against different levels of risk in relation to the risk target set out in the published regulatory guidance [3]. The work was undertaken principally in preparation for review of BNFL's Drigg post-closure safety case and authorisation.

Regulatory guidance

Disposal Facilities on Land for Low and Intermediate Level Radioactive Wastes: Guidance on Requirements for Authorisation" [the GRA]

The Agency is assessing BNFL's safety cases against the requirements set out in the UK Environment Agencies[1] publication "*Radioactive Substances Act 199 – Disposal Facilities on Land for Low and Intermediate Level Radioactive Wastes: Guidance on Requirements for Authorisation*" [the GRA][3] and more recently published UK Government guidelines on environmental risk assessment and management [4].

The GRA describes general principles for protection of the public, detailed radiological requirements, technical requirements for the safety case and guidance on the supply of supporting information. In particular, the GRA states:

- The best practicable means (BPM) shall be employed to ensure that any radioactivity coming from a facility will be such that doses to members of the public and risks to future populations are as low as reasonably achievable (ALARA).
- **After control is withdrawn**, the assessed radiological risk from the facility to a representative member of the potentially exposed group at greatest risk should be consistent with a risk target of 10^{-6} per year.
- If for the chosen design the risk to a representative member of the potentially exposed group at greatest risk is above the target of 10^{-6} per year, the developer should show that the design is optimised such that any additional measures which might reasonably be taken to enhance the performance of the chosen design would lead to increases in expenditure, whether in time, trouble or money, disproportionate to the reduction in risk. The demonstration of optimisation should also take into account any other relevant benefits and detriments.
- However, if the risk to potentially exposed groups is below the target, and the Agency is satisfied that the safety case has a sound scientific and technical basis, that good engineering principles and practice are being applied in facility design, construction, operation and closure, then no further reductions in risk need be sought.

Regulatory decisions will not be made exclusively on quantitative estimates of risk. The post-closure safety case will also be assessed against multiple and complementary lines of reasoning as set out in the principles and requirements in the GRA. The GRA requires, for example, demonstration of the use of good engineering practice in design construction and operation of a radioactive waste disposal facility. There is also a requirement for application of good science in investigating the suitability of the site; in supporting research and development work; interpreting the resulting data; and developing safety assessment methodologies. All the separate lines of reasoning contributing to an understanding of the performance characteristics of the disposal facility and an appreciation of the robustness of the safety case will inform regulatory decisions.

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1. Environment Agencies are the combined Agency's of the UK, namely the Environment Agency (of England and Wales), the Scottish Environmental Protection Agency (SEPA) and the Department of the Environment Northern Ireland – Environment & Heritage Service.

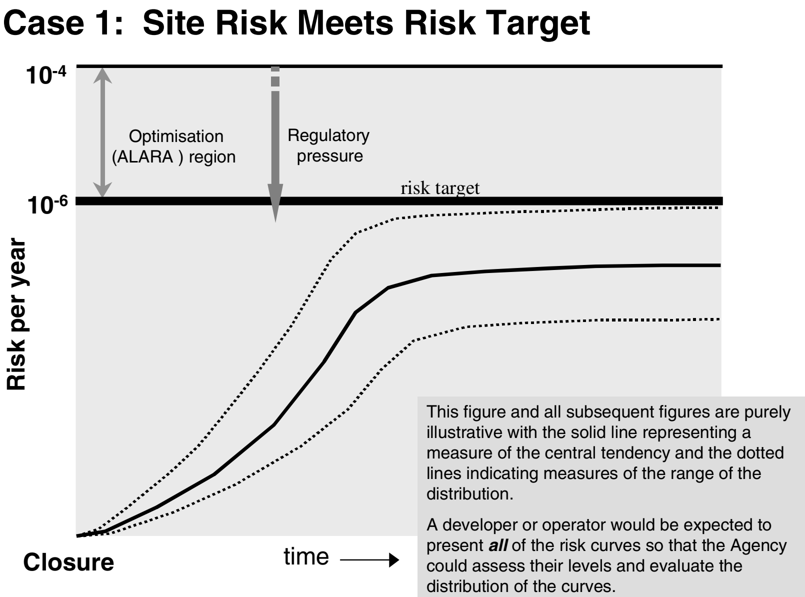
A review methodology developed and implemented by the Agency, which is firmly based on the principles and requirements set out in the GRA, is described in Duerden *et al*, 2003 [5].

In addition, the Agency has recently published results from an R&D project which investigated how post-closure safety case review outputs, and estimates of dose and risk, might be used to support regulatory decisions on the authorisation of facilities for the disposal of solid radioactive waste [6].

Guidelines for environmental risk assessment and management

The UK Government guidelines on environmental risk assessment and management [4] describe general principles that can be applied across a wide range of functions and are intended to be used in conjunction with other guidance (principally the GRA in the case of radioactive waste disposal). The guidance provides a framework for environmental risk assessment-risk management, to which specific risk guidance, such as that provided in the GRA, can refer, and allows for detailed quantitative risk assessments to be considered within a framework of other factors including social and economic costs and benefits. Decisions on risk management options or combination of options will involve a balance of risk reduction, costs, benefits and social considerations.

Illustrative Risk Results and Potential Agency Actions



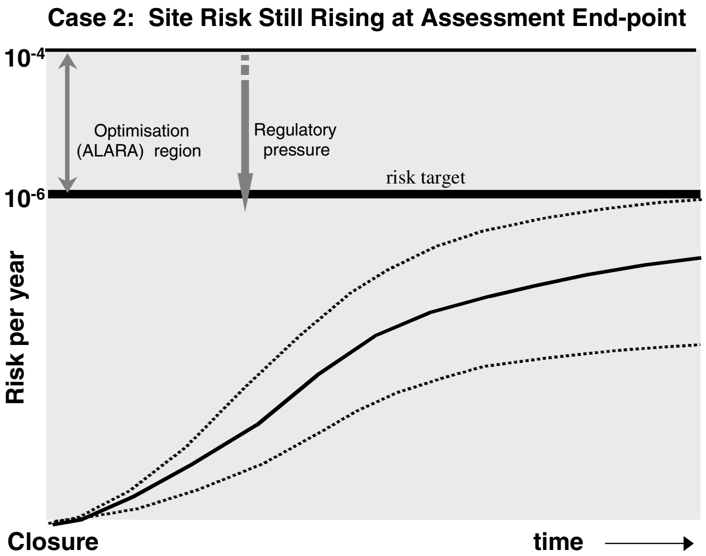
Case 1: Site risk meets risk target

The post-closure radiological safety assessment demonstrates that the site meets the risk target and the Agency has no, or only minor, concerns with respect to other aspects of the safety case. Some of the key questions that the Agency will consider here are listed in Appendix 1.

This would be a positive outcome, which nevertheless might result in a requirement for further work by the operator, for example, to:

- Ensure the safety case continues to demonstrate best practicable means (BPM) and that risks are as low as reasonably achievable (ALARA).

- Undertake further iterations of the safety case and risk assessment to incorporate scientific and technical developments:
  - To improve understanding of the risks, and of the relevant features, events and processes,
  - To reduce uncertainties.
  - To build confidence in models, calculations, assumptions and the overall risk assessment and safety case.



Case 2: Site risk meets the risk target but the risk is still rising at assessment end-point.

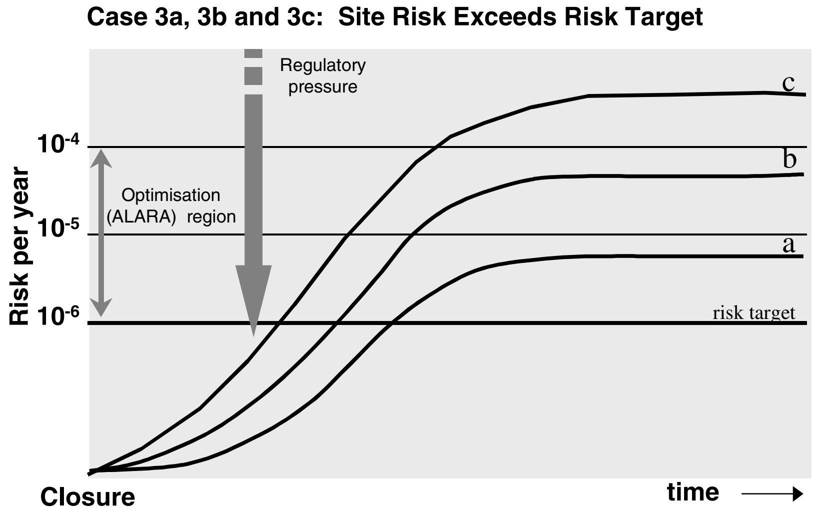
This raises a number of questions **in addition** to those in Appendix 1:

- Timescale – has the assessment been run long enough to go past any potential peak?
- What, and how plausible, is the terminating event and its timing?
- What happens if the terminating event is in the relatively near future, and what are the potential related releases? For a coastal, near surface facility, a near-future terminating event might be enhanced coastal erosion driven by climate change.
- What are the risks during and after the terminating event?

Actions that the Environment Agency might require of the operator

Same as in Case 1 but additionally, the Environment Agency might require the operator to:

- Provide the rationale underlying the selection of the terminating event.
- Undertake further iterations of the risk assessment to demonstrate that the selected timescale for the terminating event is justifiable.
- Investigate the consequences after the terminating event if this occurs in the relatively short term.



Case 3: Site risk exceeds risk target

Likely questions that the operator will need to address:

- What risk management measures can be applied to reduce overall risk and demonstrate optimisation?
- What costs are likely to be involved in reducing overall risk?
- When, and for how long, is the risk target likely to be exceeded?

Actions that the Environment Agency might require:

Same as in Case 1 but the Environment Agency might require the operator to undertake different, although not mutually exclusive, actions depending on where the assessed risks lie in relation to the regulatory risk target. Some examples of possible actions are:

Case 3a: If risk is in the range 10^{-6} to 10^{-5}/year

Demonstration of optimisation by identifying and implementing appropriate risk management measures, taking into account economic and social factors.

Case 3b: If risk is in the range 10^{-5} to 10^{-4}/year

Identification and assessment of an appropriate range of risk management options to reduce risk and associated uncertainties and to demonstrate optimisation.

Case 3c: If risk exceeds 10^{-4}/year

Identification and assessment of an appropriate range of risk management options that might be applied within a reasonable timescale and cost.

Analysis of alternative waste management options and their costs and benefits.

In this case the Agency would need to determine whether, or on what basis, development of a new facility, or disposals to an existing site, could continue, pending further investigations.

Concluding remarks

The Environment Agency seeks to ensure that radioactive waste disposal facilities provide an appropriate level of radiological protection to current and future generations. Risk provides an important indicator of post-closure performance of such a facility and risk can inform the decision-making process but on its own is insufficient. Decision making requires a safety case that provides multiple lines of reasoning based on sound science and engineering, which present clear arguments to support assessed post-closure performance.

References

[1] BNFL (2002), Drigg Operational Environmental Safety Case. Sept 2002.

[2] BNFL (2002), Drigg Post-Closure Safety Case. Sept 2002.

[3] Environment Agency, Scottish Environment Protection Agency, and Department of the Environment for Northern Ireland (1997), Radioactive Substances Act 1993 – Disposal Facilities on Land for Low and Intermediate Level Radioactive Wastes: Guidance on Requirements for Authorisation. Bristol: Environment Agency.

[4] Department of the Environment, Transport and the Regions, Environment Agency and Institute for Environmental Health (2000), Guidelines for Environmental Risk Assessment and Management. London: The Stationery Office. 88pp (ISBN 0-11-753551-6).

[5] Duerden S.L, R. Yearsley and D.G. Bennett Environment Agency, Environmental Policy – Risk and Forecasting, Guidance Note no 44. Feb 2003. Assessment of the Post-closure Safety Case for the Drigg Low-level Radioactive Waste Disposal Site. Drigg 2002 Post-closure Safety Case Review Plan.

[6] Bennett, D.G., R.V. Kemp and R.D. Wilmot, Linking Reviews of Post-closure Safety Cases for Radioactive Waste Disposal Facilities to the Process for Authorising Waste Disposal. Environment Agency R&D Technical report P3-090/TR. Dec 2003. ISBN 1-84432-242-4.

Appendix 1

Questions relating to assessed risk

Regulatory decisions will not be made exclusively on quantitative estimates of risk.

The Agency will need to determine the confidence that can be placed on quantitative estimates of risk and the contribution that the risk assessment makes to the overall understanding of the performance of the facility and the robustness of the safety case. The Agency has identified a number of questions that may help in this respect:

- Has risk been assessed using models and codes that have been adequately verified and validated (at least to present day conditions and accepted standards)?
- Do the conceptual models and parameter values underpinning the risk assessment represent acceptable descriptions of the site?
- Has an adequate range of alternative conceptual models been considered?
- Is there a clear and acceptable rationale for selection of the scenarios incorporated? What is the relative likelihood of each scenario?
- Have the scenarios giving the most likely or most representative assessments of risk been clearly identified and sufficiently well analysed?
- What are the terminating events for scenarios and associated risks (to people/environment)?
- What Features, events and processes (FEPs) are included/excluded and are these explicit in the conceptual models, codes and parameter values used to represent the site? What is the rationale behind any subsumed FEPs and is it appropriate?
- What are the uncertainties and assumptions associated with the assessed risks and are they explicit in the way the PCSC and PCRSA is presented. How robust are the underlying assumptions?
- How far has parameter uncertainty been explored and included in the risk assessment and is it adequate?
- Have parameter combinations leading to potential high estimated risks been adequately explored?
- What are the key factors contributing to risk and have these been adequately assessed?
- Have any low probability/high consequence scenarios been eliminated on the basis of their low probability and, if so, is there a sound justification for their elimination?
- Which parts of the assessment are robust? In which areas is there less confidence? In which areas is there greatest uncertainty? Where is there scope for continued improvement and confidence building?

PROPOSED REVIEW OF CURRENT REGULATORY SAFETY CRITERIA FOR THE HLW

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Research question

In line with a general international trend to move for many high risk activities to a more risk-informed management of the underlying hazards involving all stakeholders, the issue of how to provide a high degree of transparency in order to ensure commensurability and consistency in the approaches is high on the research agenda.

This paper considers the case of assessing the risks[1] from a specific "risk activity", i.e. the long-term storage of high level radioactive waste (HLW) in a deep geological formation.

Further, in order to provide consistent and systematic insights in the similarities and main differences among the existing different technical approaches on how to assess HLW risks, this paper proposes to:

- develop a generic template that allows to capture, map and communicate in a consistent way the existing large variety of current approaches, and
- to perform on the basis of this template a systematic review of current HLW risk assessment approaches as recommended or prescribed in various countries.

If successful, the results of the proposed work would not say whether the risks originating from specific nuclear waste repositories are acceptable or not, but contribute:

- to better communication of these risks among all stakeholders; and
- to their more consistent mapping and cross comparison.

Relevance of the issue

The safety assessment of HLW repositories is quite peculiar within the risk assessment community. Firstly, it inherits the basic steps, methods and know-how of the classical safety/risk assessments for nuclear power plants. Secondly, the specific sources of hazard are well known and

1. Following ISO-IEC Guide 51, "safety" is understood here as "freedom from unacceptable risk", and risk as the combination of the probability of an event and its (undesired) consequence (see also footnote 2).

bounded, not as, for example, in the case of the chemical industry where the screening and identification of the potential hazard sources is often the main challenge for modelling. And, last but not least, the degree of international cooperation during the last, at least, fifteen years has been very intensive, and has achieved some background implicit harmonisation in the approaches.

During the last years there has been a large collaboration among different countries dealing with the HLW problem to get deeper insights about different ways to establish regulatory safety criteria, sharing knowledge and experience, usually under the umbrella of international organisations such as IAEA and OECD, in addition to the EC. In some cases risk-based criteria are proposed, in other cases non-risk based ones. Even among those proposing risk-based criteria there are significant differences, for example some of them are based on mean values (and their evolution versus time), others on the exceedance of probabilities. In some regulations, risk-based and non-risk based criteria are combined.

In spite of the harmonisation already achieved, some relevant differences among different national approaches remain, and this paper proposes that the study of these differences is a relevant issue at this stage.

Some potential sources of discrepancies shall be mentioned in the following, clearly non-exhaustive list:

- A potentially main difference between different regulations is the framework approach chosen. It could be a probabilistic or a more deterministic one. In a probabilistic approach, uncertainties are explicitly tackled, and extensive efforts are dedicated to their characterisation and propagation. In a deterministic approach, uncertainties are also considered, but in a different way: Usually, most of the effort is put either on the finding of a central case (best estimate output) or on the finding of a worst case (worst case analysis). In some cases, there is a combination of deterministic and probabilistic elements in the same overall approach.
- For these different approaches, different types of safety criteria could be considered. Some magnitudes used to set these criteria are purely probabilistic (e.g. a risk criterion in the sense of ICRP), while others could be used in different ways to set either probabilistic or deterministic criteria. For example, safety criteria could be set on individual doses, on collective doses or on risk. Additionally, ancillary performance indicators, such as the concentration of pollutants in water, integrated releases of pollutants in a given time frame, fluxes or flows could also be considered.
- In the case of a probabilistic approach, for some specific measures, the safety criteria could be based on different statistical measures, such as the mean, the median or some percentile (typically 95% or 99%).
- Different regulatory bodies consider different time scales during which safety should be demonstrated, usually periods of 10^4, 10^5 and 10^6 years are considered. Moreover, in some cases regulations also differentiate between different time scales in order to set safety criteria. Perhaps doses or risks could be used for the short term, while “softer” performance indicators like concentrations or flows could be used for long-term periods.
- The safety criteria considered so far in this paper are related to the performance of the entire system. Usually, however, the system is divided in three main parts: The near field, the far field and the biosphere. Some regulations could impose some additional criteria to the performance of some of these barriers (essentially the first two), or to some of its components, such as the canister or the clad as parts of the near field.

- Event scenarios play a fundamental role in HLW safety assessments ("performance assessments"). They are related to the "what can go wrong" component of risk.[2] In some approaches, the analysis of some specific scenarios could be prescribed, in other cases the screening criteria are also considered, either based on likelihood or on consequences or even on a combination of both. Further, human intrusion scenarios could play an important role in some approaches.
- Safety criteria and performance indicators can be, and in many cases are, aggregated measures, summing up the effect of many different radionuclides and different scenarios into single plots or numbers. Non-aggregated results could also be demanded to provide further insights into the model.

In different regulations, any of these elements (and presumably many more) could be considered in a different level of detail.

To further harmonise current approaches, it is proposed to study in depth their different underlying criteria and to benchmark the different approaches on this basis. That benchmarking could also take into account additional comparison criteria, such as the consideration of different types of uncertainty, different time scales, ability to uncover risk dilution, provision of relevant information to all stakeholders, etc.

JRC has performed in the past various benchmark exercises on risk assessment approaches for major hazardous activities, including the entire life-cycle of energy technologies,[3] and is currently organising together with several institutions from Europe, USA and Japan a network on reviewing risk regulations from different industry sectors for the purpose of providing support to policy DGs.[4] The proposal briefly summarised in this discussion paper could represent one of the contributions to this network.

3. Proposed benchmarking method

As mentioned, the main working method would be development of a generic template that allows capturing, mapping and communicating in a consistent way the existing variety of current approaches, and performance of a systematic review of current HLW risk assessment approaches on this basis.

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2. That corresponds to the well-known triplet definition of risk, saying that in order to answer the question "What is the risk?" it is necessary to answer three subsidiary questions: What can go wrong? How likely is it? What are the consequences? (S. Kaplan, B.J. Garrick, "On the Quantitative Definition of Risk", Risk Analysis, Vol. 1, No. 1, 1981).

3. Past JRC benchmark exercises include the ones on various PSA-related issues, such as common cause failures, human reliability analysis, expert judgement, etc.

4. RISKREG network; further informations can be obtained from the authors.

The main underlying assumptions of this approach are:[5]

1. Risk assessment is a process accomplished by carrying out a series of distinct steps.
2. These steps can be decomposed and hierarchically organised to as fine an operational level as is needed to collect and communicate information on the nature of a specific risk assessment with the desired level of understanding.
3. The elements of the hierarchy can be defined generically enough to be inclusive of most approaches to risk assessment.
4. Each operational step in the risk assessment process should be addressed in some fashion regardless of whether addressing it is either an explicit operation requiring great technical sophistication or an implicit assumption requiring virtually no affirmative action.

A way how to map out the process of risk assessment is by looking at a number of factors based on steps common to a range of risk assessment approaches. For example, four elements could describe the major elements of risk assessment:

- hazard identification;
- release/exposure scenario;
- hazard/subject interaction (i.e. dose/response);
- and likelihood.

Within each element, sub-elements, categories, and descriptors capture the details of the different approaches used to assess risk. All the ideas shown in Section 2 of this paper provide preliminary hints to design such a hierarchy. Authorised individuals from within a network of interested institutions enter data into the system, usually experts in a particular law, regulation, or case study.

Expected outputs

By assessing existing differences w.r.t. current practice in regulatory end points for nuclear waste repositories between European and other countries, the outcome of the proposed project would mainly be to draw lessons/recommendations for future development needs so that a holistic concept for EU policy support could be developed.

Summary

This paper presents the concept of a proposed project on reviewing current regulatory safety criteria for the HLW and shall be considered a discussion document to identify interested parties and to further develop possible project tasks.

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5. I. Rosenthal, A.J. Ignatowski, C. Kirchsteiger, "A Generic Standard For The Risk Assessment Process", in: Special Issue of the Safety Science magasine on International Workshop on Promotion of Technical Harmonisation on Risk-Based Decision-Making, Pergamon Press, Elsevier Science, Oxford, Vol. 40 (Nos.1-4), February 2002, pp. 75-103.

USE OF RISK INFORMATION IN REGULATORY REVIEWS

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Introduction

The regulatory framework for licensing any high-level waste repository at Yucca Mountain in the United States, calls for appropriate use of risk information to ensure operational safety during the pre-closure period and long-term safety during the post-closure period. This paper focuses on the post-closure period. Regulations in the Code of Federal Regulations (CFR), Title 10, Part 63, apply to any repository at Yucca Mountain and envision use of probabilistic methods to develop quantitative risk information. Accumulated engineering and scientific experience at Yucca Mountain and analog sites and quantitative risk information from studies conducted by the implementer, regulator, and others are combined to formulate "risk insights," which are then used to plan and execute regulatory reviews. The U.S. Nuclear Regulatory Commission (NRC) and the Center for Nuclear Waste Regulatory Analyses (CNWRA) recently consolidated the knowledge gained during several years and developed such risk insights for the potential repository at Yucca Mountain. This paper discusses the types of risk information used to generate risk insights and how the risk insights will be used in regulatory reviews. A companion paper presents more details on sensitivity analysis methods used to generate risk information.

Types of risk information

NRC and CNWRA developed a computer code, the TPA code [1], to estimate the long-term performance of a potential repository at Yucca Mountain for the nominal and disruptive scenarios. Three scenario classes are analysed with the TPA code: (i) nominal scenario, which includes seismicity; (ii) faulting; and (iii) volcanism. Eventual failure of the waste packages and transport of radioactive waste with the groundwater over time constitute the nominal scenario. Faulting and volcanic disruption of the repository are examples of disruptive scenarios. The consequences from each scenario are weighted by their probabilities of occurrence to yield a contribution to the total system risk. The faulting scenario was determined to not make significant contributions to the total system risk and is not discussed further. Total system performance analyses and system-level sensitivity analyses result in quantitative risk information. Different types of risk information and the resulting risk insights from that information are presented next.

Understanding is gained on the expected behaviour of the total system as a function of time and its sensitivity to parameters, assumptions, and model formulations.

- *Radionuclide contributions*. Total system performance analyses show most of the radiological dose to a receptor within 10 000 years after permanent closure of the repository can be attributed to the low-retarded, long-lived radionuclides Tc-99 and I-129

[1, Figure 3-35; 3, Figure 5(c)]. Within 100 000 years, a moderately retarded radionuclide, Np-237, dominates.

- *Pinch-point analyses*. For the nominal scenario, radionuclide releases from the engineered barrier subsystem within 10 000 years are attributed to the small fraction of waste packages assumed to have defects (i.e., juvenile failures). Evaluation of radionuclide releases from the unsaturated and saturated zones shows Np-237 and Pu-239 are delayed significantly in the saturated zone [2, Figures 3-27 and 3-31].
- *Parameter sensitivity analyses*. Parameter sensitivity analyses on the nominal scenario show the system performance is sensitive to the retardation coefficient for Np-237 in the alluvium unit of the saturated zone [2, Table 4-10]. Parameter sensitivity analyses on the volcanic disruption scenario show the greatest sensitivity to the airborne mass load parameter above a fresh ash deposit.
- *Alternative conceptual models*. Substantial effects are observed on the system performance for the nominal scenario when different transport assumptions from those used in the basecase are applied [2, Figure 3-38]. The largest increases in dose are associated when retardation is assumed not to occur for Pu, Am, and Th, which supports the high significance for retardation in the alluvium unit of the saturated zone. For the nominal case, a passive film exists on the waste packages. When passive conditions are assumed absent for a fraction of the waste packages, the radiological dose increases substantially. For the volcanic disruption scenario, the alternative conceptual model for magma flowing along drifts significantly increases the number of waste packages damaged and the related consequences compared with the nominal case model for a vertical conduit. Another study determines the number of waste packages damaged in a volcanic eruption is potentially significant to the estimated risk [3, Table 2].
- *Component sensitivity analyses*. Component sensitivity analyses show substantial individual contributions to waste isolation are provided by the waste package, unsaturated zone, and saturated zone [2, Figure 6-2]. Further investigation determines most unsaturated zone performance is attributed to the capability of the unsaturated zone above the repository for reducing the amount of water contacting the waste package [2, Section 6.4.1].

Example risk insights

Risk insights are conclusions drawn about the significance of a specific physical component to waste isolation. The rating (high, medium, low) of significance to waste isolation is based on three criteria: (i) potential to affect waste packages, (ii) potential to affect radionuclide release from the waste form, and (iii) potential to affect radionuclide transport through the geosphere and biosphere. The risk insights are derived from the results of quantitative risk information.

Based on the risk information presented previously, the following are presented as examples of risk insights with high significance to waste isolation:

- Persistence of a *passive* film on the waste package.
- Retardation in the saturated zone alluvium.
- Inhalation of resuspended contaminated volcanic ash.
- Number of waste packages damaged by volcanic disruption.

Conversely, closure welding defects on the waste package, such as flaws that could promote other degradation processes leading to early failure, are limited to a small fraction of the total waste packages and are assigned a low significance to waste isolation.

Application of risk insights in regulatory reviews

The guidance document for licensing reviewers is the Yucca Mountain Review Plan [4]. This plan instructs reviewers to base the depth of their review activities on the risk significance of the aspect (e.g., feature, event, or process) being reviewed. The overall risk-informed review philosophy is to audit every aspect of the license application and define the depth and scope of detailed reviews on individual aspects commensurate with their risk significance. The application of risk insights for a risk-informed review philosophy is discussed next using two examples.

One risk insight presented previously is that the estimated long life of the waste package is predicated on the persistence of a passive film on the metallic components and the absence of electrochemical conditions leading to accelerated corrosion rates of the waste package materials. Based on quantitative analyses and other evidence that indicate the overall repository performance is highly dependent on stability of the passive oxide, this aspect is rated as highly significant to waste isolation. In the risk-informed regulatory approach, a review of aspects related to the passivity of waste package materials will require greater scrutiny and resources. The extent of the technical basis required from the applicant on aspects with high significance to waste isolation would be much greater than for those aspects with low significance.

Another risk insight is that waste package defects are of low significance to waste isolation. Any license application for a high-level waste repository at Yucca Mountain must satisfy the requirements of the NRC regulation at 10 CFR Part 63. Adequate technical bases are required for all technical areas (even those areas with low significance to waste isolation). Therefore, if the U.S. Department of Energy shows that closure welding processes have a minor impact on waste isolation, then the staff may conduct a simplified review focusing on bounding assumptions [4, Section A1.3.3].

In closing, risk insights evolve as the design changes and as the system-level understanding matures. New analyses yielding additional or updated risk information may result in changes to the risk insights for a particular technical area. As part of a risk-informed program, new information must be gathered from recent analyses to periodically re-evaluate the risk insights and identify any changes.

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References

[1] Mohanty, S., T.J. McCartin, and D.W. Esh (coordinators) (2000), "Total-system Performance Assessment (TPA) Version 4.0 Code: Module Descriptions and Users Guide (Revised)." San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses.

[2] Mohanty, S., *et al.* (2002), "System-Level Performance Assessment of the Proposed Repository at Yucca Mountain Using the TPA Version 4.1 Code." CNWRA 2002-05. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses.

[3] Bechtel SAIC Company (2002), LLC. "Risk Information to Support Prioritisation of Performance Assessment Models." TDR–WIS–PA–000009. Rev. 01 ICN 01. Las Vegas, Nevada: Bechtel SAIC Company, LLC.

[4] NRC. NUREG–1804 (2002),"Yucca Mountain Review Plan." Rev. 2. Washington, DC: NRC.

WORKING GROUP 3

PRACTICAL APPROACHES AND TOOLS FOR THE MANAGEMENT OF UNCERTAINTY

THE ISSUE OF RISK DILUTION IN RISK ASSESSMENTS[1]

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Introduction

This paper explores an issue that was first highlighted more than 20 years ago during an inquiry concerning the Sizewell B nuclear power station in the UK. In the probabilistic safety assessment for this plant, the proponent had apparently reduced its estimates of risk by admitting to increased uncertainty about the timing of certain events. This situation is counter-intuitive, since an increase in uncertainty about the factors contributing to safety would be expected to lead to less confidence and hence to greater risk. This paradoxical situation was termed "risk dilution" and it has been a topic of interest to reviewers of safety cases since. The recent international peer review of the Yucca Mountain performance assessment[2] concluded that there was a potential for risk dilution in the assumptions and calculations presented.

The next section describes how assumptions about the timing of events and other aspects of an assessment may lead to risk dilution, and this is followed by two examples based on recent performance assessments. The final section discusses how potential problems can be identified in safety cases, and the types of response that a regulator might adopt as a result.

How can risk dilution occur?

A general definition of risk dilution is a situation in which an increase in the uncertainty in the values of input parameters to a model leads to a decrease in calculated risk.

The general cause of risk dilution is an overestimation of the spread of risk in space or time: risk dispersion might be a better name. Systems with a high degree of natural dispersion will be less susceptible to risk dilution than those giving rise to consequences that are localised in space and time.

There are several ways in which risk dilution can arise, each of which produces slightly different effects:

- Event timing.
- Spatial effects.
- Parameter Correlation.
- Parameter Distributions.

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1. The work reported in this paper has been funded by SSI and SKI, and the support of Björn Dverstorp (SSI) and Eva Simic (SKI) is acknowledged.
2. IAEA and NEA, An International Peer Review of the Yucca Mountain Project TSPA-SR, 2002

The potential significance and regulatory responses to these different sources of risk dilution are also somewhat different, and so they are described separately below.

Event timing

The way in which the timing of events is treated in safety assessments is perhaps the most common reason that risk dilution is recognised as a potential issue of regulatory concern. The type of events that may require consideration in performance assessments include the onset of different climate conditions, the initiation of faulting in the geosphere, canister failure, and intrusion into the repository or a contaminant plume. All of these types of event have been considered in different probabilistic assessments using various methods.

For some types of event, such as changes in climate, there is extensive knowledge about past changes which allows for some assumptions to be made about extrapolating the occurrence of similar events into the future. For other types of event, particularly those relating to human activities, knowledge of the past does not provide a model for extrapolation into the future, and the most reasonable assumption that can be made is that future events will take place at random times.

In addition to imposed events, systems can exhibit "emergent" events, such as the arrival of a contaminated plume from a repository to the biosphere. There is no fundamental difference between an emergent or imposed event as far as the potential for risk dilution is concerned.

Simulating events at random in a probabilistic assessment means that each simulation will have a different history of events. If the event frequency is very low then the probability of an event occurring at a similar time in more than one simulation becomes very small. The overall significance of this in terms of the expectation value for dose or risk, and the potential for risk dilution, is dependent on how the consequences of the event affect the overall performance and, most importantly, the time over which these consequences persist.

If the event being simulated is one that initiates a new set of boundary conditions or has some other effect that persists for a long period, then the effect of different histories may be small. For example, the propagation of a new fault that provides an alternative pathway for radionuclides may be modelled as an event taking place at a random time. However, although the time at which the fault is formed is likely to be different in each simulation, there is a cumulative effect so that after some particular time faulting will have been simulated in the majority of the simulations. The expectation value of risk will change steadily over the period in which more and more simulations have the new conditions. This change may properly reflect the uncertainty in the time at which a fault might occur.

If the event initiates a change that is short-lived (compared to the frequency or range of possible initiation times), then the effect of different time histories may be much more significant. For these types of event, there is no cumulative effect in terms of consequences, and the effect of the event does not appear in a greater number of simulations at later times. Instead, the expectation value at any given time is derived from many simulations not affected by the event concerned and a few simulations with the effect. This is the situation that gives rise to risk dilution, because the peak value of mean consequence, which is the usual measure of risk, may be significantly lower than the mean value of the peak consequence from each simulation. We call the ratio between them the "Risk Dilution Ratio".

Spatial effects

When a potential exposure arises, for example, by accessing a contaminated plume through a well, there is a potential for risk dilution. Even if the plume location and concentration could be predicted precisely (of course, it cannot), the uncertainty in the location of wells needs to be treated with care. In a region where wells are common, it can be argued that the probability of a well being present is unity and so only the peak concentration is relevant. In a region where wells are rare, credit might be taken for the low likelihood of any well accessing the plume. In cases where wells will be present but not necessarily for the whole time, the "correct" approach is unclear – falsely taking credit for a probability of less than unity could be thought of as risk dilution. In general, any exposure that arises through human actions occurring at specific locations that are uncertain has the possibility of leading to this type of risk dilution issue.

There are other spatial effects that can lead to an undue reduction in risk but that are not risk dilution as such. In particular, the selection of inappropriate compartment sizes in models can lead to excess mixing and hence to an underestimation of concentrations. Thus, an inappropriate modelling assumption might lead to a reduction is risk. There would also be a reduction in the consequence of a deterministic case. Such problems should be avoided in the normal process of selecting and checking model assumptions.

Parameter correlation

If all of the parameters sampled in an assessment are independent, then consequences corresponding to the entire parameter space are possible. If, however, there are correlations between parameters, then some parts of parameter space will represent invalid combinations and the consequences of such combinations should not be used in calculating risk. The correlated parameters may, for example, determine the timing of an emergent event and the size of the consequence – ignoring the correlation might give impossible combinations of timing and consequence.

Ignoring known parameter correlations is equivalent to increasing the level of uncertainty, and so risk dilution can occur if the consequences from invalid parameter combinations are consistently low. However, as with the use of inappropriate pdfs (probability distribution functions) discussed below, it is also possible that invalid combinations will lead to high consequences and hence to an over-estimation of risk.

The best method for avoiding this cause of risk dilution is to account for parameter correlations within the parameter definitions and sampling methods used. Various approaches are available, depending on the parameters concerned, their distributions and the extent of the correlations, although care is required to avoid an undue reduction in the level of uncertainty when a correlation is imposed.

An alternative approach that has been used in some assessments is to apply only limited correlations at the sampling stage, but then to examine the output to determine whether the parameter combinations that have most effect on the expectation value are realistic. Although a close examination of the results should be a part of the analysis of all assessment calculations, determining whether sampled conditions are realistic or unrealistic is a subjective process. Eliminating high consequence cases on the basis of such judgements, and thereby reducing the overall expectation value of dose or risk, may not be transparent and could introduce an unintentional bias to the results. A further, serious, drawback of this approach is that the same level of scrutiny will probably not be applied to all sets of sampled conditions. This means that unrealistic conditions that result in low consequences are likely to be retained, possibly leading to risk dilution.

Parameter distributions

This type of risk dilution is perhaps the most readily avoided, because its cause is readily understood. It arises when the pdfs used to generate sets of parameter values are inappropriately biased towards the regions of the distribution leading to low consequences. Given a direct correlation between parameter value and the calculated consequence, this type of risk dilution arises if the sampled pdf is more negatively skewed than appropriate.[3]

There is no reason why pdfs should not be skewed. Indeed for parameters that cannot have negative values, a strongly skewed distribution is an accurate reflection of the uncertainty. When pdfs are supported by observations or experimental results, significant risk dilution from the use of inappropriate distributions is less likely to be an issue than when pdfs result from expert judgement or elicitation, although care is still required to avoid the inclusion of inappropriate observations.

A key concern when eliciting distributions is the phenomenon known as anchoring, whereby experts focus on a narrow range of values and underestimate uncertainty. Underestimating parameter uncertainty by defining pdfs that are too "narrow" will lead to an underestimate of uncertainty in the overall performance measure (dose or risk). Facilitators therefore encourage experts to think carefully about circumstances that may give rise to larger or smaller values than their initial estimates. The tendency toward anchoring and the consequent probing may lead analysts to extend the range of pdfs in order to compensate. It is this process of *ad hoc* increases in uncertainty that could lead to risk dilution. In practise, the converse effect of generating too high a consequence may also occur and lead to "risk amplification".

In summary, risk dilution through the inappropriate definition of parameter pdfs is only likely to be significant in a few circumstances. Undue pessimism arising from over-estimated levels of uncertainty is considered to be a more likely consequence of inappropriate parameter pdfs.

Is risk dilution a concern?

The preceding discussion has identified a number of ways in which risk dilution could occur in assessments of the long-term performance of facilities for radioactive waste. These are based on somewhat theoretical arguments which do not provide an indication of the potential significance of the effects in real assessments. Similarly, the recent international peer review of the Yucca Mountain performance assessment (NEA/IAEA, 2002) concluded that there was a potential for risk dilution, but neither the developer nor the reviewers established its possible significance. In this section, therefore, we provide two examples based on typical calculations for a repository for radioactive waste, with the aim of showing if there is indeed cause for regulatory concern if assessments are based on inappropriate assumptions or approaches.

An example based on SR97 involving event timing

One of the cases considered in SKB's SR 97 study was that of an initially failed canister, with a pin-hole that suddenly becomes much larger at some later time (this enlargement is the event of interest). This case was used by Hedin as the basis for the development of an analytic approximation[4] and was recently used as the basis for a code intercomparison exercise between AMBER and

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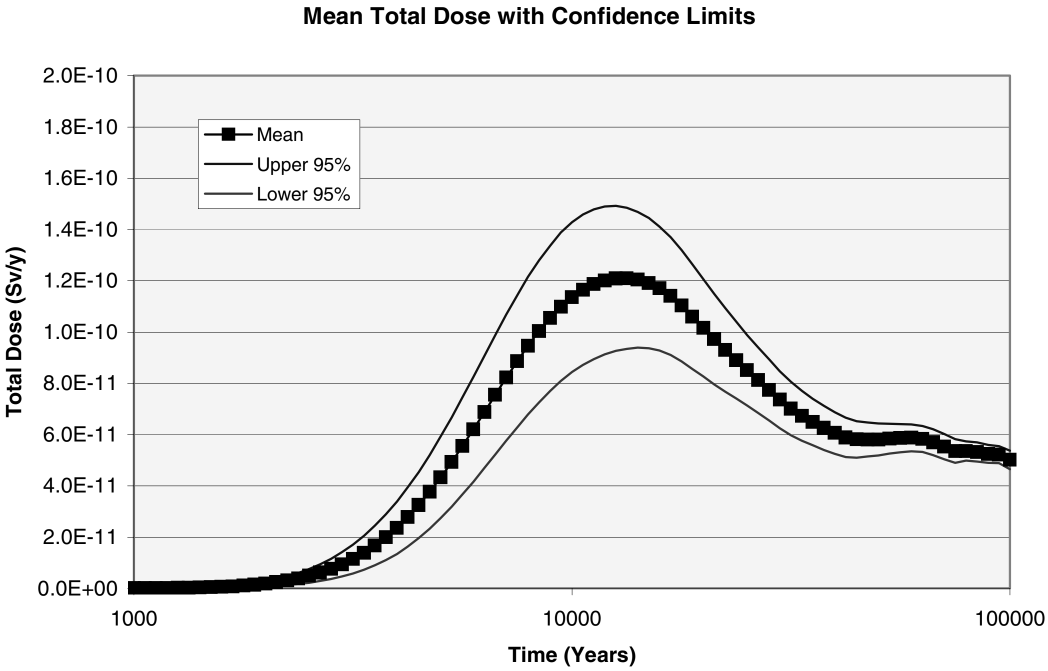
3. Similarly, inappropriate positive skewness will lead to risk dilution for parameters having an inverse correlation with calculated consequences.

4. A Hedin, Integrated analytic radionuclide transport model for a spent nuclear fuel repository in saturated fractured rock, Nucl Technol 2002; 138(2); 179-205.

Ecolego.[5] This is a full model, with release from spent fuel, release through the pinhole, diffusion in a bentonite buffer, release to a fracture, transport through the geosphere and migration in a biosphere.

Rather than attempt a full probabilistic analysis (the Hedin and intercomparison studies were deterministic), we focus on the timing of the enlargement event. In the original case this occurs after 20 000 years. In order to simplify the calculations, only four radionuclides were retained, those that give the highest consequences at early times: C-14, Ni-59, I-129 and Cs-135. The total biosphere dose was used as the measure of consequence. A probabilistic case was run with the time of enlargement sampled with a log-uniform distribution between 1 000 and 100 000 years (this distribution was invented for the purposes of the current illustration). A 100 sample run was made using AMBER. The mean consequence was plotted as a function of time and the peak consequence for each sample was stored.

Figure 1: **Mean total dose for the SR 97 example with enlargement time sampled**



5. P Maul, P Robinson, R Avila, R Broed, a Pereira and S Xu, AMBER and Ecolego Incomparisons using Calculations for SR 97, SKI Report 2003:28, SSI Report 2003:11.

Figure 2: **CDF of peak total dose for the SR 97 example with enlargement time sampled**

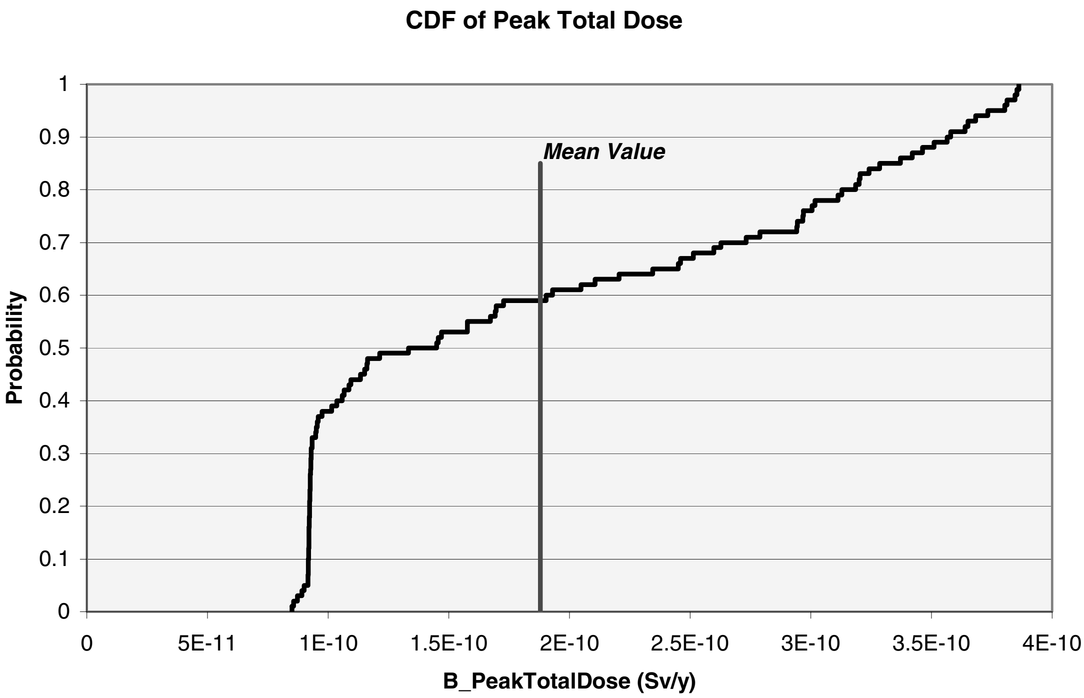


Figure 1 shows the mean consequence versus time, with a peak value of 1.21E-10 Sv/y. Figure 2 shows a CDF of the peak consequence, with a mean value of 1.88E-10 Sv/y. Thus, the risk dilution ratio here is 1.55.

This small ratio seems to be due to the highly dispersive nature of the SR 97 system. The pin-hole release model provides a lot of spreading, as does the release from the bentonite to the fracture. Finally, matrix diffusion spreads the consequences further. Thus, each individual sample gives a dispersed result leaving little scope for risk dilution.

To test that this was indeed the case, the model was altered to reduce the dispersion. Matrix diffusion was eliminated and the pin-hole release model was changed so that the radionuclides passed quickly into the buffer once the pin-hole had enlarged. With these two changes, the peak mean consequence becomes 2.62E-9 Sv/y and the mean peak consequence becomes 9.10E-9 Sv/y. Thus the risk dilution ratio becomes 3.47. This figure might be a cause of concern if risks were very close to a target value, but not otherwise.

Even with these two dispersive barriers disabled, the risk dilution ratio is less than an order of magnitude, suggesting that significant risk dilution in this type of system is unlikely.

An example arising in SFR assessments involving spatial effects

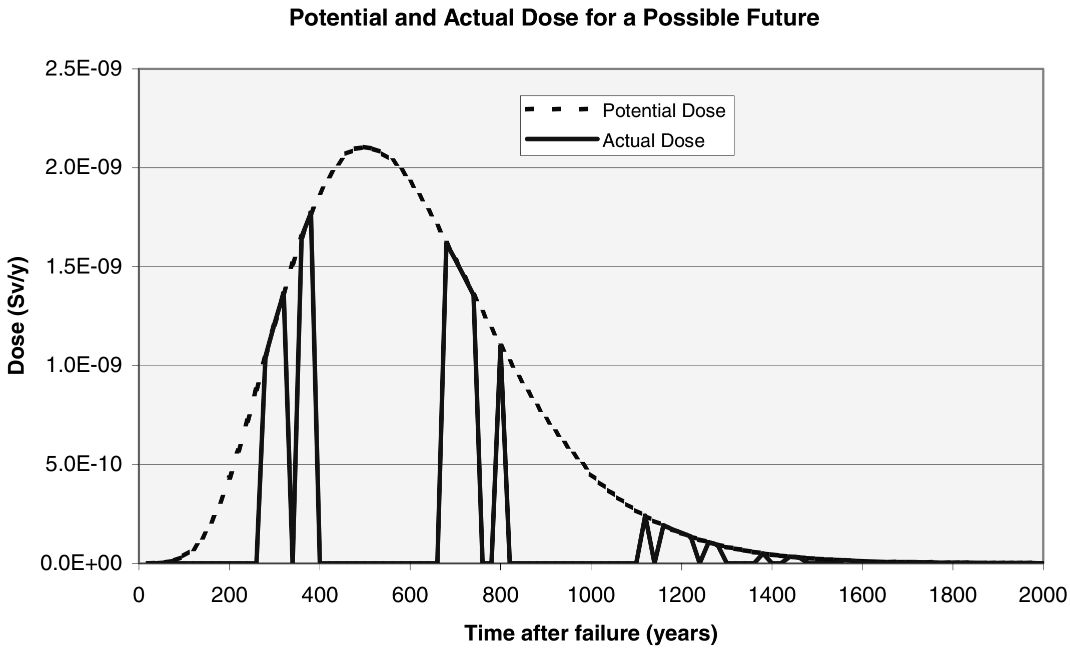
One possible pathway for doses to arise from SFR is for wells to access a plume of contamination downstream of the repository. Well drilling rates suggest that on average there will be 0.1 wells in the plume (the plume size is about 0.2 km^2 and the well density 0.5 wells/km^2).[6]

SKB calculate the risk from this pathway as the consequence when a well is present multiplied by 0.1.[7] Is this the correct approach?

Wells have a limited period of operation, so the average value of 0.1 effectively means that there is a well in the plume 10% of the time. Thus, a typical dose versus time curve might look like Figure 3.

Clearly, the average peak dose over such futures is close to the peak potential dose value, rather than a tenth of this. This appears to be a case of risk dilution.

Figure 3: **Potential dose and actual dose for a possible future in the well scenario**



6. U. Kautsky (editor), The Biosphere today and tomorrow in the SFR area, SKB Report R-01-27.
7. SKB, Slutförvar för radioaktivt driftavfall, SFR 1, Slutlig säkerhetsrapport, Svensk Kärnbränslehantering AB, Stockholm, 2001.

Regulatory responses

The preceding discussion of the ways in which risk dilution could arise provides useful indicators of the ways in which it can be reduced or avoided. In this section, these indicators are brought together and are expressed in a form that could be useful in developing regulations or regulatory guidance.

In general terms, regulators can respond in three ways to the identification of a potential issue:

- Prescriptive regulations could be promulgated to ensure that the issue does not arise in a safety case or other documentation submitted to the regulator.
- Regulatory guidance could be issued to ensure that the developer is aware of the issue and therefore takes steps to avoid or minimise its effects.
- Review criteria could be used to ensure that the regulator considers the potential effects of the issue at the time of assessing or reviewing a safety case.
- There is overlap between these responses, especially with respect to review criteria which are likely to be necessary even if regulations or guidance are issued.

The choice between these various regulatory responses is related as much to the established style of regulation in a particular country as it is to the issue concerned. Because of the various ways in which risk dilution may arise in assessments of long-term performance, it may not be possible to establish prescriptive regulations or guidance on how it should be avoided. The following discussion therefore concentrates on more general guidance and review criteria. The examples discussed above provide some support for these discussions, but there is scope for additional calculations to provide further information and perhaps a quantitative basis for criteria.

In all cases, the presentation of distributions of consequences in addition to risk calculations is to be encouraged as an aid to general understanding.

Event timing

Regulators recognise that assessment calculations are a means of demonstrating system understanding and analysing uncertainties as well as showing numerical compliance with a risk or dose criterion. Furthermore, there are many other aspects of a safety case that play a part in demonstrating safety. The regulator would expect a safety case to include sufficient information for reviewers to be able to determine whether risk dilution was an issue. For example, the regulator would expect all assessment results to be available. These would show whether there were high consequence events in the majority of simulations. Without a corresponding increase in expectation value, such a pattern would indicate the potential for risk dilution.

A specific requirement would be a calculation of the risk dilution ratio, the ratio between the mean value of peak consequence and the peak value of mean consequence over a number of time-scales. Where results suggest that there is a potential for risk dilution, for example a ratio of more than 10, the onus must be on the proponent to explain and justify the approach adopted. It is likely that the conceptual models and assumptions responsible for such differences would be readily identifiable. Sensitivity studies would support this identification. A specific exploration of the causes of dispersion in the model could be a useful way of improving understanding and identifying possible sources of risk dilution.

Where a potential for risk dilution is identified because of uncertainties over the timing of events, the regulator could require calculations using a number of fixed times. These might not necessarily be used for comparison with a numerical criterion, but would help in understanding the importance of key uncertainties and consequently aid decision-making.

Spatial effects

The appropriate treatment of spatial effects is intimately entwined with the identification of potentially exposed groups (PEGs). Any guidance or review criteria from regulators concerning risk dilution must therefore be compatible with guidance and criteria concerning PEGs. This paper is not directly concerned with the definition of PEGs, but the potential for risk dilution does indicate that care is required in separating out the uncertainties concerning the location of a contaminant plume or release of radionuclides to the biosphere, the location of the PEGs (in both space and time), and the characteristics and behaviour of the PEGs.

The use of risk as an end-point for safety assessments can encourage the use of probabilities to characterise all sources of uncertainty and the presentation of a single value or distribution as a result. The many sources of uncertainty relating to the treatment of spatial effects and PEGs mean that such an approach may obscure assumptions that give rise to risk dilution. Where a potential for risk dilution is identified because of uncertainties over spatial effects, the regulator is likely to require calculations using a number of different assumptions. These might not necessarily be used for comparison with a numerical criterion, but would help in understanding the importance of key uncertainties and consequently aid decision-making.

Correlations

Assessment documentation must include an explicit consideration of parameter correlations. Form-based documentation provides a useful means for ensuring that the conclusions are available for review. The regulator would expect strong correlations to be taken into account through parameter definition or sampling methods. The exclusion of any identified correlations should be justified through sensitivity studies or similar reasoning. Any post-analysis assessment of the reasonableness of parameter combinations should consider all cases and not only those resulting in high consequences.

Distributions

Assessment documentation must include an explicit description of the basis for all parameter pdfs. Form-based documentation is a useful means of making relevant information available for review. The regulator would expect full documentation of any expert judgement and elicitation involved in establishing pdfs, including the identification of appropriate experts, the information and training provided to experts and the experts' justification for the pdfs.

Conclusions

This paper has described a number of ways in which risk dilution could occur in performance assessments of radioactive waste management facilities. The majority of these can be avoided through a systematic approach to developing a safety case and undertaking assessment calculations. Appropriate documentation is key in providing assurance to the regulator and other stakeholders that modelling assumptions have not led to significant under-estimation of risks.

The treatment of future events in probabilistic assessments remains an issue of regulatory concern. Where there is no information available, the assumption that such events might take place at random is unlikely to be a conservative assumption. A comparison between the peak value of mean risk and the mean value of peak risk over a number of timescales is the only prescriptive requirement that is likely to be generally applicable. It may be appropriate to develop additional criteria on a site-by-site basis. Where calculated risks are close to numerical criteria, for example, regulators are likely to require sensitivity studies regarding the timing of events, PEG characterisation, parameter correlations and pdfs, and other modelling assumptions

It seems from the example presented here that risk dilution is unlikely to be of concern in situations where only one barrier in a multiple barrier system is affected by an event – the other barriers will generally provide dispersive processes that will prevent highly localised consequences. Situations where consequences are more localised, are the most likely candidates for risk dilution.

RISK ASSESSMENT USING PROBABILISTIC STANDARDS

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Introduction

A core element of risk is uncertainty represented by plural outcomes and their likelihood. No risk exists if the future outcome is uniquely known and hence guaranteed. The probability that we will die some day is equal to 1, so there would be no fatal risk if sufficiently long time frame is assumed. Equally, rain risk does not exist if there was 100% assurance of rain tomorrow, although there would be other risks induced by the rain. In a formal sense, any risk exists if, and only if, more than one outcome is expected at a future time interval.

In any practical risk assessment we have to deal with uncertainties associated with the possible outcomes. One way of dealing with the uncertainties is to be conservative in the assessments. For example, we may compare the maximal exposure to a radionuclide with a conservatively chosen reference value. In this case, if the exposure is below the reference value then it is possible to assure that the risk is low. Since single values are usually compared; this approach is commonly called "deterministic". Its main advantage lies in the simplicity and in that it requires minimum information. However, problems arise when the reference values are actually exceeded or might be exceeded, as in the case of potential exposures, and when the costs for realising the reference values are high. In those cases, the lack of knowledge on the degree of conservatism involved impairs a rational weighing of the risks against other interests.

In this presentation we will outline an approach for dealing with uncertainties that in our opinion is more consistent. We will call it a "fully probabilistic risk assessment". The essence of this approach consists in measuring the risk in terms of probabilities, where the later are obtained from comparison of two probabilistic distributions, one reflecting the uncertainties in the outcomes and one reflecting the uncertainties in the reference value (standard) used for defining adverse outcomes. Our first aim is to delineate the approach, in comparison with the deterministic approach, to define the entities involved in the assessment and their relationship. The second aim is to identify possible strategies for deriving and combining the probability distributions. In the explanation we will use a terminology that is related to the exposure to radionuclides in the environment.

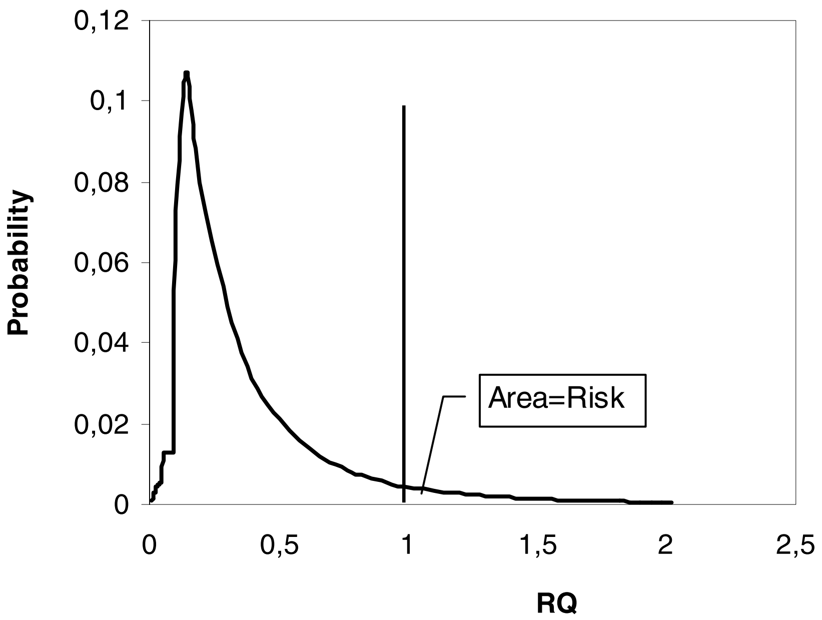
Probabilistic versus deterministic assessments

Lets consider the commonly applied risk quotient (RQ), which can be defined as the ratio between the exposure to a radionuclide in the environment and the reference value adopted for this radionuclide (equation 1). In a deterministic assessment, single estimates are used for the exposure and the reference value. If these were conservatively chosen and a value below 1 was obtained for the RQ, then it can be assured that the probability of the exposure exceeding the reference value is low, i.e. the risk is low. Obviously, the exposure and reference levels should be expressed in the same units, for example in units of dose, intake rates or environmental concentrations.

$$RQ = \frac{Exposure}{reference\ value} \qquad \text{(Equation 1)}$$

The essence of a "fully probabilistic approach" is to treat both the *Exposure* and the *reference value* (equation 1) as random variables. In this case, the RQ is also a random variable that can be described with a probability density function, commonly known as the "risk profile" (see Figure1). Hence, a deterministic RQ is just one value among the universe of all values than the RQ can possibly take. The probability that the RQ is above 1 (indicated area in Fig.1) is a quantitative measure of the risk. In contrast, the deterministic approach provides only a qualitative risk estimate.

Figure 1. **Example of probability density function corresponding to the Risk Quotient commonly known as the "risk profile". The area under the curve for RQ>1 is a quantitative measure of the risk**

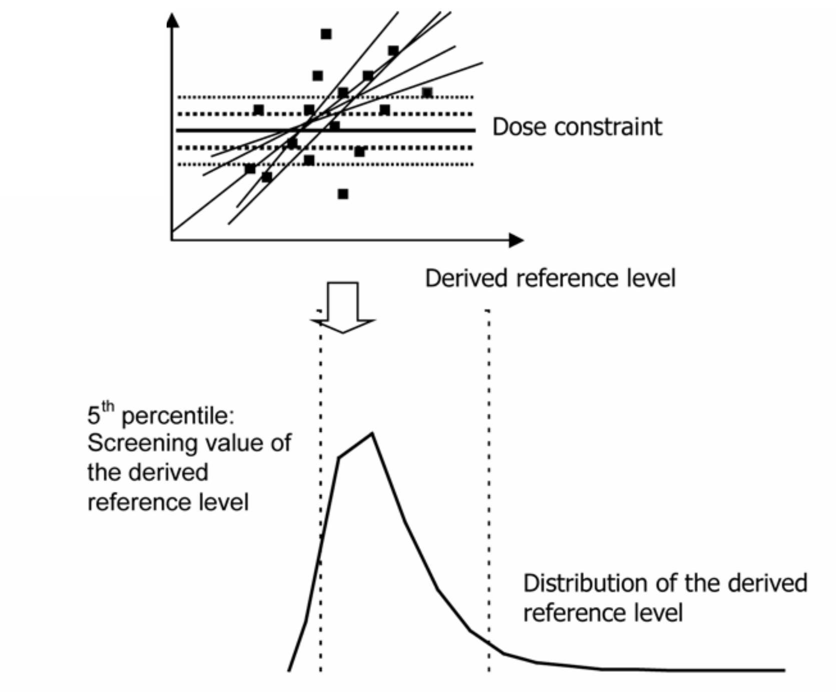


In the deterministic approach, normally, conservative values are used in equation 1. Given the multiplicative nature of the model, a substantial magnification (positive bias) of the conservatism may take place. For this reason, values of RQ close to or above 1 will carry very little information about the risks. A common way to deal with this problem is to carry out assessments in tiers. This means that more realistic quotients are estimated whenever a conservative assessment yielded RQ > 1. This approach could be seen as a simplified version of a probabilistic approach. In any case, the interpretation of the results would require knowledge about the distribution of the exposure and the reference value. For example, using mean values in equation 1 is meaningful only if the magnitudes follow a normal distribution, which is rarely the case.

Derivation of probability distributions for the standards

The derivation of probability distributions for the Exposure is rather straightforward, and we will not, therefore, address it in this presentation. The reference value (standard) should allow identifying adverse values of the exposure. The standard could, for example, be related to the effects of radiation and obtained from studies of dose-effects relationships and might be expressed in terms of a source related dose constrain that takes in to account possible exposure to regional and global sources. Derived reference levels, expressed for example as environmental concentrations or fluxes, could also be used. These could be obtained from existing quantitative relationships between the primary dose limits and the derived magnitudes. The quantitative relationships could be based on empirical data or could be derived with the help of mathematical models. A simple procedure for derivation of reference values, commonly known as the bootstrap method, is illustrated in Figure 2.

Figure 2. **Probability distribution for the reference value (standard) obtained from the quantitative relationship between the dose and a derived reference level using the bootstrap method**



Note that even if a single value is used for the primary reference level, a probability distribution is obtained for the reference value, reflecting uncertainties in the quantitative relationship between the primary and reference levels. Once the probability distribution of the derived reference level has been obtained, single values corresponding to different percentiles of the distribution could be used in deterministic assessments. For example the 5% of the distribution could be used in screening assessments.

The primary reference values, for example the dose constrains, can also be considered as random variables. If the method illustrated in Figure 2 is applied for obtaining derived reference values, then a probability distribution could be used for the dose constrain (represented by several levels of the dose constrain in Figure 2). This would reflect the variability among individuals in the sensibility to radiation, our imperfect knowledge of the dose-response relationships, the variability in the background radiation, etc.

Measuring the risk

To measure the risk the probabilistic distributions of the *Exposure* and the *Reference Value* has to be combined through equation 1. If simple analytical expressions for the probability distribution are available, then variance propagation can be applied for the deriving the risk profile. When analytical expressions are not available for the distributions, or when they cannot be combined analytically, these can be combined using Monte Carlo analysis.

The basis for a Monte Carlo analysis is straightforward: point estimates in a model equation are replaced with probability distributions, samples are randomly taken from each distribution, and the results tallied, usually in the form of a probability density function or cumulative distribution.

Advantages and disadvantages

A "fully probabilistic approach" provides a more complete quantitative characterisation of the uncertainties and is less likely to include a bias, than the more simple deterministic approach. Even with a tiered approach, each deterministic assessment provides single values for estimates of exposure from a given pathway. Such single-value risk estimates do not provide information on the variability and uncertainty that may be associated with an estimate.

When combined with sensitivity analyses, the probabilistic approach allows a more informative "what-if" assessment of the impact on the risk estimates of a change in a variable or a group of variables, thus providing a cost-effective tool for making risk management decisions.

This approach also permits more constructive comparisons of remedial alternatives when diverse attributes must be compared to systematically reduce the baseline risk. This includes comparing alternatives or intervening measures that could also cause other risks.

Finally, the use of probabilistic standards facilitates deriving standards. For example standards in terms of concentrations may be derived from standards in term of dose, even when there is variability and uncertainty in the relationship between the doses and the concentrations.

The main disadvantage of the probabilistic approach is that time and effort is required in order to set up the database and document the rationale for the probability density functions. The distribution patterns for some variables are often not definitively known, requiring the use of credible professional judgment or costly site-specific studies or data collection efforts. Also, the impact of inter-dependencies between or among variables may be difficult to quantify if their co-relations are not well known, as it is often the case.

In view of the above discussion, the probabilistic approach appears to be most appropriate when the risks are not trivial, for example in situation where the risk might be above or slightly below the acceptable level of risk or hazard, and where the costs for risk reduction are potentially high.

METHODOLOGY FOR RISK ASSESSMENT OF AN SNF REPOSITORY IN SWEDEN

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Introduction

The Swedish Nuclear Fuel and Waste Management Co., SKB, is currently pursuing investigations at two candidate sites for a spent nuclear fuel repository. An application to build a repository at one of the sites is planned for 2008, if the geologic conditions are found suitable. A methodology for the risk based assessment of post closure safety for the application is being developed [1]. This paper presents some aspects of the methodology related to the quantification of risk.

The repository will be of the KBS 3 type where copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at typically 500 m depth in saturated, granitic rock, Figure 1. The primary safety function of the concept is complete long-term isolation of the waste, achieved by the integrity of the copper canisters and supported by the strength of the cast iron insert. Should isolation for any reason be breached, the ceramic waste form, the damaged canister, the buffer and the host rock provide a considerable retarding capacity – the secondary safety function.

The principal compliance criterion states that the annual risk of harmful effects must not exceed 10^{-6} for a representative member of the most exposed group. The annual risk is to be obtained by multiplying the calculated **mean dose**, taken over all possible exposure situations, by the stipulated constant $\gamma = 0.073$ per Sievert so that the risk limit corresponds to a dose limit of approximately 14 μSv/yr.

The dual purposes of the assessment are to *i*) evaluate compliance and *ii*) provide feedback to design development, to SKB's R&D program, to further site investigations and to future safety assessment projects. While the first purpose could possibly be achieved by a pessimistic approach regarding uncertainties, the latter requires a more elaborate evaluation of the impact of various types of uncertainty on the assessment end-points, most notably the annual risk.

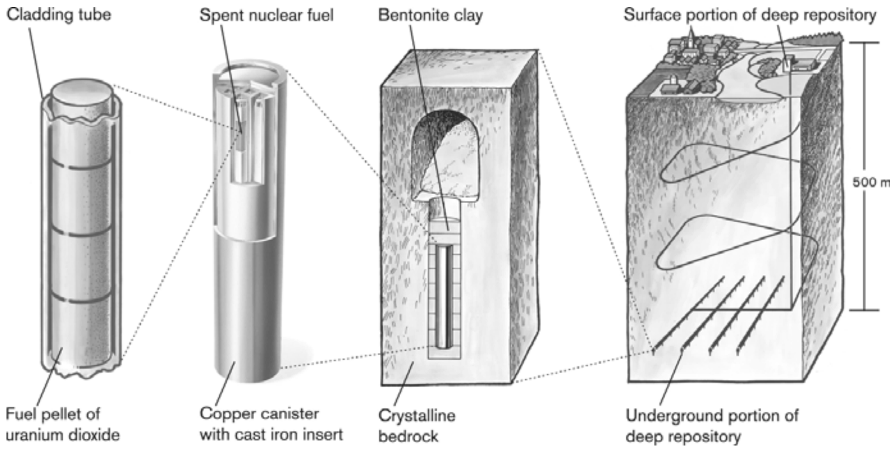
Approach to risk calculations

The approach to the numerical risk calculations is in short the following:

- Break down possible evolutions of the system into a number of representative scenarios and estimate scenario probabilities.
- Evaluate every scenario by studying the system evolution during the one million year assessment period.

- If evolution indicates breaching of isolation, calculate radionuclide transport and dose consequences probabilistically for barrier conditions derived from the system evolution.
- Add, using scenario probabilities as weighting factors, **the time dependent mean doses** from the different scenarios and convert to risk.

Figure 1. **The Swedish KBS 3 concept for geologic deposition of spent nuclear fuel**



The approach is thus **disaggregate** in the sense that, for each scenario, system evolution is studied and discussed and, if isolation is breached, a subsequent account is given of radionuclide transport and dose consequences. On the order of ten scenarios are envisaged, further sub-divided into variants.

The calculated result will to some extent be **a deliberate overestimate** of risk since many uncertainties will be treated pessimistically in the assessment. This will likely apply to several of the scenario probabilities and also to a number of processes which are favourable for safety but for which the understanding or modelling capability is insufficient for quantification. This is fully compatible with the purpose of assessing compliance, provided that there are sufficient safety margins to meet the compliance criterion also with the pessimistic assumptions. However, regarding the purpose of providing feedback, the omission or pessimistic treatment of some factors may yield a biased view of the importance of other factors treated more thoroughly. This needs to be acknowledged in any discussion of feedback in the safety report.

The possibilities of assigning realistic scenario probabilities are often limited. Regarding e.g. future climate, both repetitions of past 130 000 years glacial cycles and an alternative where this development is considerably perturbed by a greenhouse effect can be envisaged. While the two are mutually exclusive, both must be regarded as likely. In the risk summation, it will though be observed that the summed consequence of a set of mutually exclusive scenarios can, at any point in time, never exceed the maximum of the individual scenario consequences.

Scenarios involving **direct intrusion** into the repository will be assessed **separately** and excluded from the risk summation, according to Swedish regulations.

Quantification of input data uncertainty

While all the several hundred input data must be quality assured, only a limited sub-set are uncertain to an extent critical for the safety evaluation, thus requiring a detailed quantification of uncertainty. These data will be identified by sensitivity analyses of calculation results using input data ranges from earlier assessments. The results will be used to allocate resources to the determination of the final input data set. A common template for the discussion of input data is being developed. The nature of the uncertainty (epistemic/aleatoric) and correlations to other input data will be addressed. For critical parameters which are difficult to assess from experimental data, a formal elicitation procedure may be considered, involving experts in the relevant field as well as safety analysts. Input data will be expressed e.g. as an estimated range, possibly with a most likely value within it, based on which uniform, triangular or normal distributions (or the corresponding log distributions) could be selected. A number of different distributions will be tried to test sensitivity to these aspects. Other input data will be obtained as probability density functions from separate probabilistic analyses of e.g. the spatially varying transport properties of the host rock or the frequency of canister welding defects.

Sensitivity analyses

Sensitivity analyses will be applied to the calculated dose distribution at different points in time. The aim is to determine *i*) which uncertain input parameters give the most significant contribution to the width of the output distribution (the global uncertainty) and *ii*) the risk drivers, i.e. those uncertainties that have a significant impact on the mean value of the dose as a function of time. It has been demonstrated earlier that standardised rank regression is a suitable method for the former [2] and that conditional mean values are suitable for the latter [3].

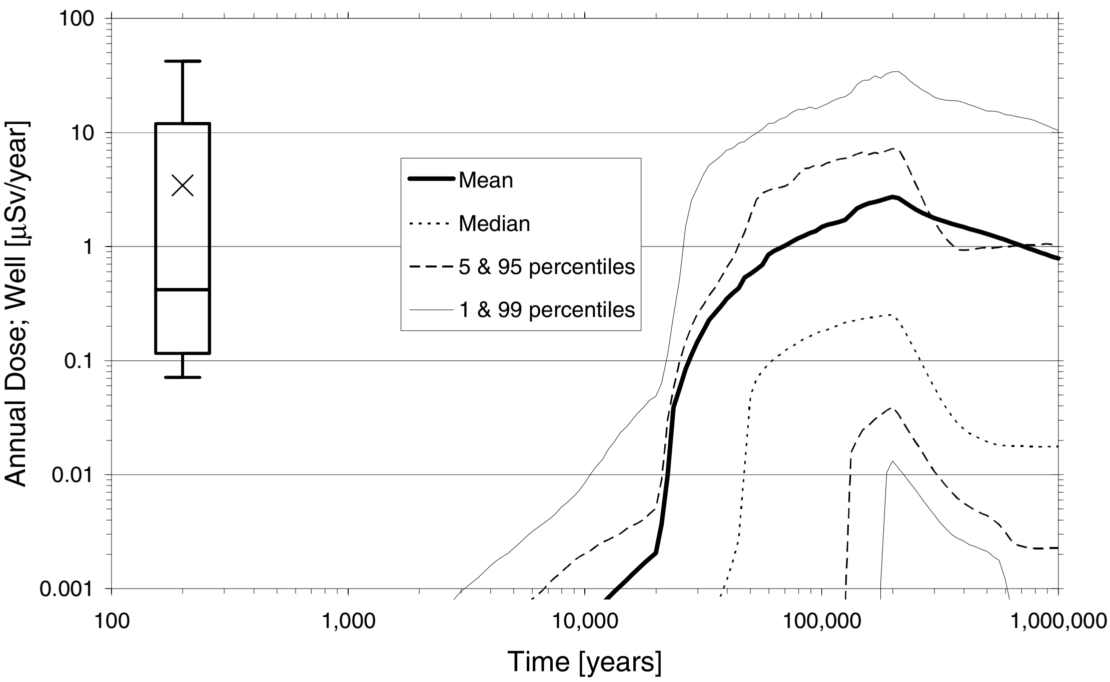
An important part of any sensitivity analysis exercise is to verify that all important sensitive parameters have been identified. This can be done *i*) by assigning constant central values to all identified sensitive input parameters keeping the full distributions for remaining input data which should yield a considerable reduction in output distribution width and *ii*) by using full distributions for only the sensitive parameters keeping others constant at central values which should yield an insignificant reduction in output distribution width.

As a complement to these more formal sensitivity analyses, it will also be discussed how the results and their sensitivities can be understood using simplified, analytical radionuclide and dose models.

Example calculation

Figure 2 shows the result of a radionuclide transport and dose example calculation developed to test quantitative aspects of the methodology. The example illustrates a scenario where all initially intact canisters maintain their integrity over the one million year assessment period despite the chemical and mechanical stresses they are subjected to. One per mille of the 4 500 canisters are assumed to have initial defects such that this leads to releases of radionuclides, starting however at a point in time which is highly uncertain. Based on extrapolation of experimental data, this onset time is in the present example assumed to be uniformly distributed between 300 and 200 000 years. Furthermore, it is pessimistically assumed that today's biosphere prevails and that all releases occur to the same well which is used at a self-sustaining farm for drinking water, irrigation etc. The input database was developed from an earlier assessment of the same system. The calculation scheme distinguishes between aleatoric and epistemic uncertainty in that canisters in the repository have position specific, correlated stochastic hydraulic variable distributions reflecting the variability of the host rock. Canister specific defect characteristics are obtained from a common distribution, reflecting the stochastic nature of failures in the canister sealing process. Epistemic uncertainty, affecting estimates of e.g. the fuel dissolution rate, is treated probabilistically where fuel in all defective canisters in a certain realisation is assigned the same value drawn from an input distribution obtained as discussed in section 2.1.

Figure 2. **Statistics of the dose distribution as a function of time, pessimistically assuming that all releases occur to the same well. The box-and-whisker to the left shows the same percentiles of the peak dose distribution and with the mean value represented by the cross.**



Treating instead all uncertainty as epistemic, i.e. assigning all defective canisters in a certain realisation the same properties, yields, as expected, the same mean dose, but also similar results for the other statistics shown in the figure, which is not necessarily expected. An alternative to be further explored would be to describe all epistemic uncertainty as intervals and to perform the risk calculation as a combination of Monte Carlo simulation and a bounding type of analysis, see e.g. [4].

The calculation was made for 17 radionuclides, however reducing this to only I-129 and Ra-226 yields an almost identical result. Furthermore, the top percentile of the distribution is almost entirely caused by Ra-226. The distribution is highly skewed since the mean is close to the 95th percentile. This is essentially a reflection of the skewness of a few important input distributions, rather than of the transformation properties of the model.

Sensitivity analyses as outlined above show that main contributors to global uncertainty are variables related to the number of initially defective canisters, the onset time of releases from these, the dissolution rate of the fuel, the transport resistance in the rock and the dose conversion factors in the biosphere for I-129 and Ra-226. The main risk drivers as identified by conditional mean analyses are the same as those contributing to global uncertainty except the dose conversion factor of I-129 and in addition a few variables related to the near field release of Ra-226.

Risk dilution

The term “risk dilution” is sometimes used to denote a situation where a higher degree of uncertainty in input parameters, i.e. a broader input distribution, leads to a lower mean value of an output entity e.g. mean dose or risk [5]. A seemingly paradoxical situation arises where less knowledge implies a more safe repository if the mean value to a highly exposed individual at a certain point in time is used as the safety indicator. Less knowledge will spread the dose over more individuals and over longer times. The total exposure to all individuals over all times could be the same or larger, whereas more distinct knowledge will “concentrate” the risk to fewer individuals and shorter periods of time. This can e.g. be the case when there is uncertainty concerning the point in time for the onset of releases from a damaged canister. The dose consequence at a certain time could then depend strongly on the assumed onset time. Averaging over alternative situations in which the onset and thus the peak dose occur at different times would reduce the resulting mean value at any point in time and more so the larger the span of possible onset times.

This effect is inherent in the concept of risk and is thus an inevitable consequence of a criterion based on risk as a function of time and where the entity to be determined is the time-dependent mean value considering all relevant uncertainties. The above effect should thus be tolerable given the Swedish regulations.

It is nevertheless interesting to elucidate and quantify risk dilution effects in the safety assessment. This can be done by comparing the peak of the mean dose curve in Figure 2 (2.7 μSv/yr occurring at approximately 200 000 years) to the mean value of the peak doses in all realisations irrespective of when they occur. This latter entity is 3.4 μSv/yr (the cross in the box-and-whisker to the left in Figure 2) which leads to the conclusion that risk dilution effects of this temporal type are not a concern in this system for these input data. This is largely due to the fact that once a canister is ruptured, releases will continue essentially undiminished for a long period of time, so that similar peak doses are obtained irrespective of the canister rupture time.

A related phenomenon concerns the biosphere development during the expected long periods of permafrost or glacial conditions. Assume that appreciable doses to man could occur only during temperate periods, and that these periods, as suggested by historical evidence relevant to Sweden, in the long run will prevail in total during about ten percent of the time but that the temporal location of these temperate intervals cannot be predicted beyond, say 10 000 years into the future. In principle this situation could be handled by simulating a number of future situations where the onsets of the temperate periods are allowed to vary randomly beyond 10 000 years. Averaging over all these results would, at each point in time beyond 10 000 years, yield a dose consequence a factor of ten smaller than that obtained during a temperate climate period. This simplistic example demonstrates another type of risk dilution, again caused by an uncertainty in the point in time of the occurrence of a phenomenon, which could in principle be compatible with the Swedish risk criterion. The effect can however be avoided in the safety assessment by assuming the same temporal sequence of climate types in each simulation or, as in the example given, a steady state biosphere.

It is also concluded that a broader input data distribution is not necessarily pessimistic, not even if it is broadened towards the high consequence end.

Conclusions

An approach to risk assessment for upcoming license applications for a spent nuclear fuel repository has been presented. The approach is adapted to the safety functions of the analysed system in that isolation potential is first analysed and then dose consequences in cases where isolation is breached. It is furthermore scenario based and disaggregate, it deliberately overestimates some aspects of risk and it handles direct intrusion scenarios separately. Input data uncertainties for probabilistic dose consequence calculations are quantified by following an established protocol, common to all input data types. In the consequence calculations, a distinction is made between aleatoric and epistemic uncertainty, global sensitivity to input data uncertainty is quantified and risk drivers are identified. Risk dilution effects are discussed and quantified. Apart for being useful for assessing compliance, the results are expected to provide useful feedback to the continued waste management program.

Finally, it is noted that risk is only one of several indicators of repository safety. Complementary indicators being considered include radionuclide concentrations in the groundwater and the flux of radionuclides to the biosphere.

References

[1] Planning Report for the Safety Assessment SR-Can. SKB Technical Report TR-03-08, Swedish Nuclear Fuel and Waste Management Co. (2003).

[2] Hedin, A. (2003), Probabilistic dose calculations and sensitivity analyses using analytic models. Reliability Engineering and System Safety 79: 195-204.

[3] Hedin, A. (2002), *Safety Assessment of a Spent Nuclear Fuel Repository: Sensitivity Analyses for Prioritisation of Research*. Proceedings of the 6th International Conference on Probabilistic Safety Assessment and Management, PSAM6. Elsevier Science Ltd.

[4] Ferson, S. and L.R. Ginzburg (1996), Different methods are needed to propagate ignorance and variability. Reliability Engineering and Systems Safety 54:133-144.

[5] NEA (1997), *The Probabilistic System Assessment Group: History and Achievements 1985-1994*. OECD, Paris.

GLOBAL SENSITIVITY ANALYSES METHODS FOR GENERATING RISK INFORMATION

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Introduction

The regulations for licensing a potential high-level waste repository at Yucca Mountain, Nevada, in the United States, call for use of risk information in demonstrating safety during the operational and post-closure periods. Regulations in the Code of Federal Regulations, Chapter 10, Part 63, for the Yucca Mountain repository [1] require application of probabilistic methods to develop quantitative risk information. Sensitivity analyses play a major role in developing quantitative risk information.

Several new sensitivity analyses methods have been developed at the Center for Nuclear Waste Regulatory Analyses (CNWRA), sponsored by the U.S. Nuclear Regulatory Commission (NRC). In this paper, three new methods applicable to Monte Carlo-based performance assessment models are described: (i) a parameter tree method, (ii) a partitioning method, and (iii) a mean-based method. The three CNWRA-developed methods belong to the class of Aglobal@ methods where sensitivity of the model outputs to changes in parameters is estimated for the entire range of values. In the discussion that follows, a *realisation* is defined as a set of input parameters, each parameter represented by a unique sampled value, and corresponding outputs predicted by the model. A convenient output typically used as a performance metric is the maximum dose for each realisation in a simulation period (the regulatory period specified in [1] is 10 000 years).

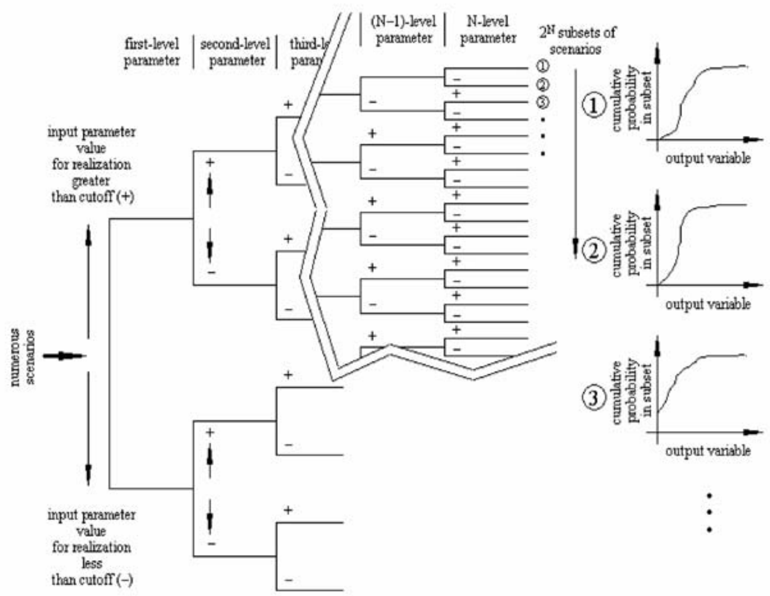
Parameter tree method

To construct a parameter tree, samples of input parameter values are treated as A+@ or Ạ@ based on the comparison of the parameter value to a branching criterion (such as the mean, median, or any percentile of the parameter distribution). The corresponding system outputs or performance metrics (e.g., maximum dose) are then aggregated into similar bins. The most important parameters are identified by applying the branching criterion, one parameter at a time, and defining a correlation between parameter branching and system output binning. A definition of such a correlation, selected as importance index I_i, is discussed in detail by Jarzemba and Sagar [2]:

$$I_i = \left| p_i^+ - p_i \right| \qquad (1)$$

p_i^+ is the probability that a realisation in the A+@ parameter branch belongs to the A+@ system output bin, and p_i^- is the probability that a realisation in the Ạ@ parameter branch belongs to the A+@ system output bin. The probabilities are estimated by counting the number of realisations satisfying the conditions. If there is no relationship between the branching of the parameter and system output, the two probabilities, p_i^+ and p_i^-, are similar, and the value of I_i is close to zero. The most important parameters are identified by sorting the importance index. A multiple level branch tree can be constructed by combining various parameters, each tree level associated with a single parameter (see Figure 1). The probability that a realisation in a given branch also belongs to the A+@ system output bin is a measure of the importance of the parameter combination. If the median of the parameter is selected as the branching criterion, the number of realisations belonging to a given branch is approximately $r/2^N$, where r is the number of realisations, and N is the number of parameters considered (i.e., the number of branching levels). A detailed application of the parameter tree approach to analyse output data produced by the Total-system Performance Assessment code for the Yucca Mountain system is available elsewhere [2].

Figure 1. **Generalised parameter tree**



Partitioning method

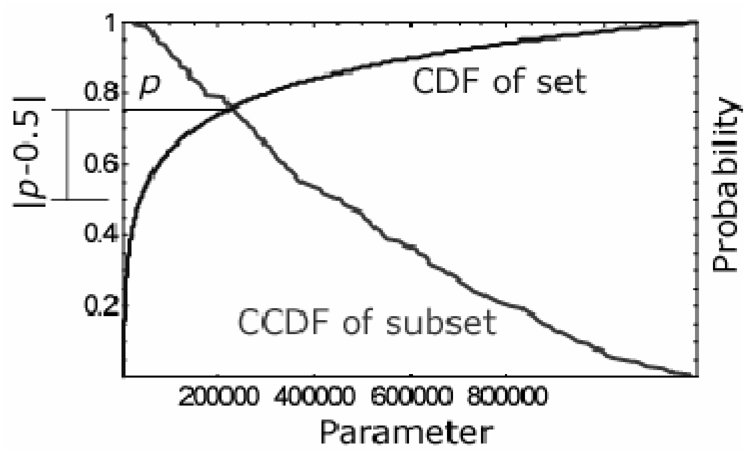
In the partitioning method, realisations also are divided into two sets depending on the comparison of a system output (e.g., maximum dose) to a threshold value (e.g., mean of the set of maximum doses for all realisations). For each parameter, the set with the fewest realisations (characteristic set) is selected, and the complementary cumulative distribution function (CCDF) of the parameter is computed. This CCDF of the subset of parameter values is compared with the cumulative distribution function (CDF) of the complete population of parameter values. The intersection in the probability axis, p, can be used to define an importance metric for the parameter (see Figure 2).

The distance away from 0.5, $|p0.5|$, is a measure of the parameter influence on the performance metric [3]. A positive value of the $p0.5$ statistic indicates a positive correlation between the parameter and the system output. A significance test for the $|p0.5|$ statistic has been derived recently [4]. The standard deviation of the p statistic, σ_n, in a random selection of n elements is:

$$\sigma_n = \frac{0.246}{\sqrt{n}} \qquad (2)$$

The collection of parameters most important to the system output is identified by sorting the |p0.5| statistic, selecting only those parameters that satisfy a criterion such as |p0.5|>2 σ_n. The partitioning method can be combined with the parameter tree method to define a robust importance index of parameter combinations, considering the subsets of system outputs (e.g., maximum doses) belonging to a particular branch. The partitioning method has been combined with the principal component decomposition to analyse outputs that are functions of time [4].

Figure 2. **Graphic description of the determination of the *p* statistic in the partitioning method**



Mean-based sensitivity method

A cumulative distribution sensitivity analysis technique was developed by Mohanty and Wu to rank influential parameters [5]. The technique was intended to estimate the response in a particular percentile of system output to changes in the first and second moments of input parameters. The unique aspect of this technique is that a single multiple-realisation Monte Carlo run is sufficient to assess the change in a particular percentile of system output. Recently, the technique was extended to estimate responses in the mean of the system output to changes in the first and second moments of an input parameter distribution [6]. The mean-based sensitivity of the system output Y on the parameter X_i is defined as

$$S_{Y_\mu} = \frac{1}{r}\sum_{j=1}^{r}\left[u_i Y\right]_j \qquad (3)$$

where r is the number of realisations, and u_i is the result of mapping parameter X_i onto a normal distribution with a zero mean and unit standard deviation. If Y is independent of changes in the mean of parameter X_i, then S_{Y_μ} is zero. A statistical significance test on the mean-based sensitivity, S_{Y_μ}, can be implemented by comparing P_i

$$P_i = \frac{S_{Y_\mu}}{\sqrt{E\left[u_i^2 Y^2\right]/r}} \qquad (4)$$

to a confidence percentile of the standardised normal distribution. Those parameters for which $|P_i|$ is greater than the confidence percentile are identified as the influential parameters. A similar sensitivity measure to that in Equation (3), based on the standard deviation of the input parameter, has been defined elsewhere [6]. The mean-based sensitivity has been applied to the analysis of maximum doses per realisation estimated with the Total-system Performance Assessment code for the Yucca Mountain system [6].

Remarks

Three sensitivity-uncertainty methods are presented. All of them are efficient in the sense that a single multiple-realisation Monte Carlo run is sufficient to generate results. Multiple methods are intended to complement the analyses of complex models for risk assessment to develop confidence that components most important to system safety are identified. The three methods discussed in this paper were created to support development of risk insights for the potential repository system at Yucca Mountain, Nevada, in the United States.

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References

[1] U.S. Nuclear Regulatory Commission (2001), Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada: Final Rule, *Federal Register*, vol. 66, No. 213. p. 55732. November 2, 2001.

[2] Jarzemba, M.S. and B. Sagar (2000), A Parameter Tree Approach to Estimating System Sensitivities to Parameter Sets. *Reliability and System Safety*. Vol. 67. pp. 89-102.

[3] Pensado, O., V. Troshanov, B. Sagar and G. Wittmeyer (2002), A Partitioning Method for Identifying Model Parameters. Probabilistic Safety Assessment and Management (PSAM6). Vol. 1. E.J. Bonano, A.L. Camp, M.J. Majors, and R.A. Thompson, eds. Kidlington, Oxford, United Kingdom: Elsevier Science Ltd. pp. 827-833.

[4] Pensado, O. and B. Sagar (2004), Sensitivity Analysis of an Engineered Barrier System Model for the Potential Repository System in the United States. Paper to be presented at the 7th Probabilistic Safety Assessment and Management (PSAM7). Berlin, Germany. June 14-18, 2004.

[5] Mohanty, S. and Y-T. Wu (2001), CDF sensitivity analysis technique for ranking influential parameters in the performance assessment of the proposed high-level waste repository at Yucca Mountain, Nevada, USA, *Reliability Engineering and System Safety*, vol. 73, No. 2, pp. 167–176.

[6] Mohanty, S. and Y-T. Wu (2002), Mean-based Sensitivity or Uncertainty Importance Measures for Identifying Influential Parameters, Probabilistic Safety Assessment and Management (PSAM6), vol. 1. E.J. Bonano, A.L. Camp, M.J. Majors, and R.A. Thompson, eds. Kidlington, Oxford, United Kingdom, Elsevier Science Ltd, pp. 1079–1085.

RISK AND UNCERTAINTY ASSESSMENT FOR A POTENTIAL HLW REPOSITORY IN KOREA: TSPA 2006

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KAERI has worked on the concept development on permanent disposal of HLW and its total system performance assessment since 1997. More than 36 000 MT of spent nuclear fuel from PWR and CANDU reactors is planned to be disposed of in crystalline bedrocks. The total system performance assessment (TSPA) tools are under development. The KAERI FEP encyclopedia is actively developed to include all potential FEP suitable for Korean geo- and socio conditions. The FEPs are prioritised and then categorised to the intermediate level FEP groups. These groups become elements of the rock engineering system (RES) matrix. Then the sub-scenarios such as a container failure, groundwater migration, solute transport, etc are developed by connecting interactions between diagonal elements of the RES matrix. The full scenarios are developed from the combination of sub-scenarios. For each specific scenario, the assessment contexts and associated assessment method flow charts are developed. All information on these studies is recorded into the web based programme, FEAS (FEP to Assessment through Scenarios.) KAERI applies three basic programmes for the post closure radionuclide transport calculations; MASCOT-K, AMBER, and the new MDPSA under development. The MASCOT-K originally developed by Serco for a LLW repository has been extended extensively by KAERI to simulate release reactions such as congruent and gap releases in spent nuclear fuel. The new MDPSA code is dedicated for the probabilistic assessment of radio-nuclides in multi-dimensions of a fractured porous medium. To acquire input data for TSPA domestic experiment programmes as well as literature survey are performed. The data are stored in the Performance Assessment Input Data system (PAID.) To assure the transparency, traceability, retrievability, reproducibility, and review (T2R3) the web based KAERI QA system is developed. All tasks in TSPA are recorded under the concept of a “Project” in this web system. Currently, FEAS, PAID, the web based QA system in associated with documentation system and the visual MASCOT-K programme are integrated into the new system, CYPRUS. Once completed the CYPRUS system will be a platform not only for the daily R&D but also as the information provider for general public. The issues of stakeholders are the key for the successful TSPA. At this moment, KAERI is working on understanding characteristics of stakeholders and the optimum solution to accommodate opinions of stakeholders over TSPA. To illustrate the safety of a Korean reference disposal system (KRDS) some specific scenarios are identified. Results show that under given conditions the safety of the KRDS suits the guidelines given by Korea Institute of Nuclear Safety (KINS), the sole regulators in Korea. Results clearly point out that the future R&D in data acquisition should be focused on the understanding of the major water conducting features (MWCF.) The integrated results of TSPA and the KRDS development will be published in 2006.

PHYSICALLY BASED PROBABILITY CRITERION FOR EXCEEDING RADIONUCLIDE CONCENTRATION LIMITS IN HETEROGENEOUS BEDROCK

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Introduction

A significant problem in a risk analysis of the repository for high-level nuclear waste is to estimate the barrier effect of the geosphere. The significant spatial variability of the rock properties implies that migrating RNs encounter a distribution of bedrock properties and mass-transfer mechanisms in different proportions along the transport paths. For practical reasons, we will never be able to know exactly this distribution of properties by performing a reasonable amount of measurements in a site investigation.

On the contrary, recent experimental studies reveal that crystalline bedrock can possess a marked heterogeneity of various physical and geochemical properties (Hakami and Barton, 1990; Siitari-Kauppi *et al.*, 1997; Xu and Wörman, 1998) that potentially may have a certain impact on the transport of RNs in fractured bedrock. Also current field investigation techniques provide only fragmentary information of the properties of the geosphere. This is a basic motivation for treating flows of water and solute elements in groundwaters by means of stochastic continuum models (Gelhar *et al.*, 1974; Dagan, 1989; Gutjahr *et al.,* 1978; Gelhar *et al.*, 1979; Gelhar and Axness, 1983).

The stochastic analysis is based on the idea that we know only certain point values of the property fields and use this information to estimate intermediate values. The probabilistic properties of the stochastic analysis are suitable input variables for risk analyses of the relevant sequence of extreme events for which empirical observations are rare or non-existing.

The purpose of this paper is to outline the implications of the stochastic approach for estimating probabilities that certain concentration limits are exceeded at discharge points from the bedrock in case of a leakage from the waste repository. The analysis is restricted to the water flow and solute transport in the bedrock alone without consideration of the full sequence of events in a full risk analysis and the Baysian statistics involved in such conditioned (and cross-correlated) event series. The focus is on the implication for the risk analysis of the auto-covariance structure in bedrock properties and uncertainty in the associated site data.

Formulation of probability criterion

The three-dimensional nature of the mass flow involves uncertainties related both to the water flow and the geochemistry of the solute transport. A possible and relevant starting point for a probability analysis is the expected value of the solute concentration at a certain control section (Dagan, 1989; Rodriguez-Iturbe and Rinaldo, 1997).

$$< c(t) >= \int_0^{\infty} c(t, \tau) g(\tau) d\tau \qquad (1)$$

in which g(τ) is the travel time probability density function (PDF) for water parcels travelling from an imagined leakage zone to the control section, τ is the residence time of an inert water parcel travelling along one of the trajectory paths, and c(t, τ) is the concentration of solute per unit volume of fracture water [kg/m^3] and t is the time [s].

A physically based analysis of the travel time PDF for water, $g(\tau)$, and the solute response function, $c(t, \tau)$, will be associated with uncertainties due to the discrete collection of data and the heterogeneous environment. According to the central limit theorem, the deviation of the estimated (sampled) expected value, $< \bar{c} >$, from the true expected value, E[<c(t)>], of an ensemble of outcomes (realisations) is normally distributed with the standard deviation Std[<c>]/$n^{0.5}$, where n is number of samples. Hence, the probability that $< \bar{c} >$ exceeds a certain limit ***C*** can be expressed as

$$p(< \bar{c} > \geq \boldsymbol{C}) = p(z \geq Z) = erfc[Z] \qquad (2)$$

in which the standardised variable z = [$< \bar{c} >$- E[<c>]]/ Std[$< \bar{c} >$], Z = [***C*** - E[<c>]]/ Std[$< \bar{c} >$]. The probability that an individual realisation exceeds the limit ***C*** can be expressed analogous to (2) under the assumption that the distribution of <c> is normal.

In this study, we will assume normal distribution of <c> and stationarity in the sense that Std[<c>] = constant regardless of time and physico-chemical processes. Hence, (2) is the criterion from which we will express the probability that the estimated concentration exceeds a certain limit, in which z = [<c>- E[<c>]]/ Std[<c>],. Furthermore, from Gauss approximation formula one may show from a discrete form of (1) and independence between g and c that

$$Var[< c(t) >] \cong \int_0^{\infty} Var[c(t, \tau)] g^2(\tau) d\tau + \int_0^{\infty} c^2(t, \tau) Var[g(\tau)] d\tau \qquad (3)$$

in which the variance operators are evaluated over the ensemble of random realisations (not e.g. the temporal variance of g and c, respectively). Consequently, the probabilistic problem is decomposed into problems of estimating the uncertainties as well as the expected values of the solute response curve on one hand and the water residence PDF on the other hand. Those problems are practically feasible based on statistical data of physical and chemical parameters of the system. Particularly, if the cross covariance between g and c can be neglected the stochastic analysis of the solute transport and the water flow can be done independently.

Stochastic -physically based formulation of flow and transport processes

Both the water flow and the solute transport are analysed based on stochastic continuum and a combination of numerical techniques and closed-form solutions. The water flow can modelled based on a discrete fracture network that is generated with known statistically properties as well as deterministic features such as observed fracture zones (Geier, 1992, 1996 and 2004). The statistical nature of the procedure calls for a need to employ Monte Carlo simulations to resolve Std [g(τ)] and E[g(τ)]. These calculations are relatively “heavy” and form a practical point of view the computer capacity sets significant limits to be noted.

The solute transport is formulated based on partial, differential equations that represent advection, matrix diffusion and sorption in the solid rock surfaces. The most relevant rock properties including fracture aperture and several matrix properties as well as flow velocity are assumed to be spatially random along transport pathways. Perturbations (random spatial variability in bedrock properties) are introduced in the coefficients to reflect an uncertainty of the exact appearance of the bedrock associated with the discrete data collection.

The mass transport is first solved in a general form along one-dimensional pathways, but the results is extended to multi-dimensional flows simply by substituting c(t, τ) in (1). A solution can be obtained in the Laplace domain for a Dirac pulse that is released at the up-stream boundary in the form of (Wörman *et al.,* 2003, Wörman *et al.*, 2004)

$$\mathrm{E}[\bar{\mathrm{c}}] = \frac{\mathrm{M}_0}{\mathrm{Q}} \exp\left[\left(-\mathrm{E}[\tilde{\beta}] + \sum_{i=1}^{N} \mathrm{a}_i \frac{\ell_i}{\mathrm{E}[\tilde{\beta}]\ell_i + 1}\right)\mathrm{x}\right] \qquad (4)$$

where the auxiliary variables $\tilde{\beta} = c_1\eta_u + c_2\eta_u\eta_h\eta_M$, $\eta_u \equiv u/\tilde{u}$, $\eta_h \equiv h/\tilde{h}$, $\eta_M \equiv \tilde{M}/M$, $M = (D_p\varepsilon_t\varepsilon(1+K_D))^{0.5}$ [m $s^{-0.5}$], $c_1 = p/u$, $c_2 = -[(2\varepsilon_t D_p)/(hu)]\alpha[1 - 2/(1+\exp(-2Z\alpha))]$, $\tilde{\alpha} = \sqrt{p(1+K_D)/[(p+k_r)(\varepsilon_t/\varepsilon D_p)]}$ and p is the Laplace variable. The series expansion method of De Hoog *et al*. (1982) by means of the MATLAB® code of Hollenbeck (1998) to numerically invert (4) to the real domain. For the solution in a network of fractures representing the bedrock, the summation is performed over 26 terms (N=26) and the variance factor a_i as well as the correlation factor l_i are defined in Table A3-1 in Wörman *et al.* (2004). The second term on the right-hand side of (4) represents the effect of the parameter variability on the expected value of c. Both a_i and l_i can be determined from statistical evaluation of data on the physico-chemical parameters of the system as demonstrated in the next section.

The variance of c can be evaluated in the Laplace domain as the square-root of the expected value E[c´c´], where c´ is the perturbation (deviating from E[c]). Wörman *et al.* (2003) showed that

$$\bar{\mathrm{c}}' = \frac{\mathrm{M}_0\beta'}{\mathrm{Q}\sum_{i=1}^{N}\mathrm{a}_i\frac{\ell_i}{\mathrm{E}[\beta']\ell_i+1}} \exp\left(-\mathrm{E}[\tilde{\beta}]\mathrm{x}\right)\left(1-\exp\left(\sum_{i=1}^{N}\mathrm{a}_i\frac{\ell_i}{\mathrm{E}[\tilde{\beta}]\ell_i+1}\right)\right) \qquad (5)$$

$$\begin{aligned}\beta' = {} & c_1\eta'_u + c_2E[\eta_u]E[\eta_M]\eta'_h + c_2E[\eta_u]E[\eta_h]\eta'_M + c_2E[\eta_M]E[\eta_h]\eta'_u + c_2E[\eta_u]\eta'_M\eta'_h + \\ & + c_2E[\eta_M]\eta'_u\eta'_n + c_2E[\eta_u]\eta'_u\eta'_M + c_2\eta'_u\eta'_M\eta'_h - c_2E[\eta_u]Cov[\eta_M\eta_h] - c_2E[\eta_M]Cov[\eta_u\eta_h] \\ & - c_2E[\eta_h]Cov[\eta_u\eta_M] - c_2Cov[\eta_u\eta_h\eta_M] \qquad (6)\end{aligned}$$

Consequently, we now have a complete coupling between statistical treatment of data, physically based analyses of the flow and transport processes as well as the probabilistic criterion subject to the risk assessment.

Application to site specific data

The empirical basis for site specific example is taken with respect to geology and geohydrology from the safety assessment exercise performed by the Swedish Regulatory (SKI, 1996) with the use of data from Äspö Hard Rock Laboratory. The flow analysis follows the approach described in Wörman *et al.* (2004). Data on parameter variability on a fracture scale in the Äspö bedrock was taken from the studies of Xu and Wörman (1998; 1999) and Hakami (1995). The expected values of the parameters were:

$D_e = 10^{-13}$	$[m^2/s]$
$D_p = 10^{-10}$	$[m^2/s]$
$\varepsilon = 0.004$	[-]
$k_d = 0.008$	$[m^3/kg]$
$k_r = 10\text{-}10$	[1/s]
x = 500	[m]
h = 0.0064	[m]
u = 50	[m/y]
L = 0.1	[m]

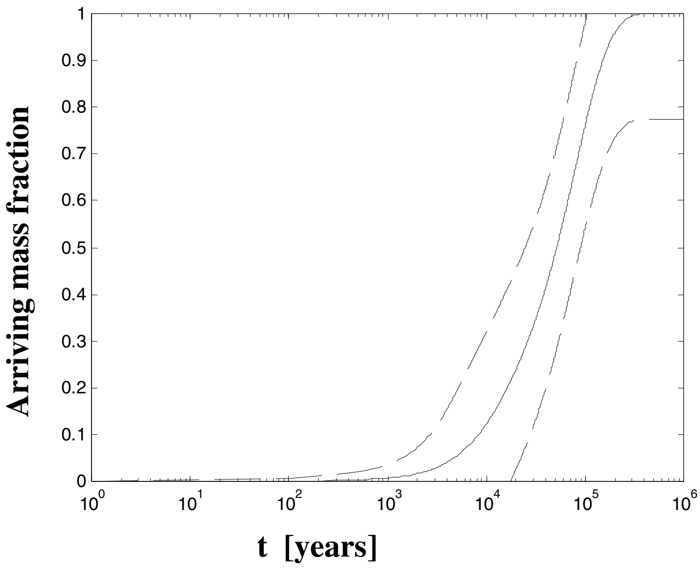
Geostatistics of the matrix property M, aperture and flow velocity for single fractures were obtained from Äspö crystalline rock in a one-meter scale (Xu and Wörman, 1998; Xu *et al.*, 2001; Hakami, 1995). The statistics of the matrix property are obtained from direct measurements, whereas the velocity and aperture variation are evaluated along flow trajectories arising in Monte Carlo flow analyses with fractures with spatially variable aperture (Xu *et al.* 2001). The information of both statistics and parameter values are summarised in Table 5 in Wörman *et al.* (2004).

From the flow analyses it was clear that there is a notable correlation length in both flow velocity and fracture aperture that is longer than the size of the fracture. However, due to limited computer capacity no Monte Carlo simulations were performed for the flow. In this illustrative example the probabilistic components are limited to the first term on the right-hand side of (3).

Figure 1 shows the mass fraction arriving (cumulative concentration) at the boundary surfaces of the 5 km x 5 km x 1 km calculation domain. As can be seen the confidence intervals defined in terms of ± one standard deviation is up to several hundred percents. Qualitatively, the first term on the right-hand side of (3) is $Std[<c>]/E[<c>] \approx 2$. Hence, as an example based on (2), the probability that the concentration exceeds one standard deviation is about 16%.

The time corresponding ton 50% mass recovery falls within the prediction interval 10^4-10^5 years and, in this interval, there is an uncertainty about timing of about one order of magnitude due to the uncertainty of the rock properties.

Figure 1. **Accumulated solute mass resulting from a pulse of a reactive solute traveling through a fracture network, in which the solid line denotes the expected cumulative breakthrough curve (BTC), the dash lines denote plus/minus one standard deviation**



Discussion

The exact concentration limit relevant in a risk analysis depends on several conditioned factors such as failure of repository canister as well as change of climate, hydrology and ecology. The aim of this tentative study is to demonstrate a methodology by which we can estimate the probability that concentration limits for radionuclides in heterogeneous bedrock are exceeded. The proposed method is based on a physical formulation of the under laying mechanisms of the water flow and solute transport, a stochastic representation of system properties and a geostatistical interpretation of site specific data. Such a combined theoretical and empirical approach is particularly recommendable as components of risk analysis involving events for which direct observations are rare or non-existing.

References

Dagan, G, 1989. *Flow and Transport in Porous Formations*, Springer-Verlag, Berlin.

De Hoog, F.R., J.H. Knight, A.N. Stokes (1982), An Improved Method for Numerical Inversion of Laplace Transforms, J. Sci. Stat. Comput., 3(3), 357-366.

Geier, J.E. (1996), Discrete-Fracture Modelling of Äspö Site: 3, Predictions of Hydrogeological Parameters for Performance Assessment, (SITE-94) SKI Report 96:7, Swedish Nuclear Power Inspectorate, Stockholm, Sweden.

Geier *et al.* (1992), Discrete-fracture network modelling, Finnsjön, Phase 2, SKB Technical Report 92-0x.

Geier, J., (2004), "Discrete-Feature Model for Flow and Transport in Fractured Crystalline Rock: DFM Code Version 1.0 Technical Description and User Documentation," SKI Report 03:xx.

Gelhar, L.W., P.Y. Ko, H.H. Kwai and J.L. Wilson (1974), Stochastic Modelling of Groundwater System, Rep. 189, R.M. Parsons Lab. for Water Resour. and Hydrodyn., Mass. Inst. of Technol., Cambridge.

Gelhar, L.W., A.L. Gutjahr, R.L. Naff (1979), Stochastic Analysis of Macrodispersion in a Stratified Aquifer, Water Resources Res., 15(6), 1387-1397.

Gelhar, L.W., C.L. Axness (1983), Three-dimensional Stochastic Analysis of Macrodispersion in Aquifers, Water Resources Res., 19(1), 161-180.

Gutjahr, A.L., L.W. Gelhar, A.A Bakr, and J.R. MacMillan, (1978), Stochastic Analysis of Spatial Variability in Subsurface Flows, 2. Evaluation and Application. Water Resources Res. 14(5), 953-959.

Hakami, E. (1995), Aperture Distribution of Rock Fractures. Doctoral Thesis, Department of Civil and Environmental Engineering, Royal Institute of Technology, Stockholm.

Hakami, E., N. Barton (1990), Aperture Measurements and Flow Experiments Using Transparent Replicas of Rock Joints, Proc. Int. Symp. Rock Joints, Loen, Norway, Eds. Barton and Stephansson, Balkema, Rotterdam, The Netherlands, 383-390.

Hollenbeck, K. J. (1998), INVLAP.M: A Matlab Function for Numerical Inversion of Laplace Transforms by the De Hoog Algorithm, http://www.isva.dtu.dk/staff/karl/invlap.htm

Rodriguez-Iturbe, I., A. Rinaldo, (1997), *Fractal River Basins*, Cambridge University Press, Cambridge, United Kingdom.

Siitari-Kauppi, M., A. Lindberg, K.H. Hellmuth, J. Timonen, K. Väätäinen, J. Hartikainen and K. Hartikainen (1997), The Effect of Microscale Pore Structure on Matrix Diffusion æ a Site-specific Study on Tonalite. J. Contaminant Hydrology, 26, 147-158.

SKI (1996) SKI SITE-94, Deep Repository Performance Assessment Project. SKI Report 96:36. Swedish Nuclear Power Inspectorate, Stockholm, Sweden.

Wörman, A., S. Xu, B. Dverstorp (2003), “Kinematic Analysis of Solute Mass Flows in Rock Fractures with Spatially Random Parameters”, Journal of Contaminant Hydrology, 60: 2003, 163-191.

Wörman, A.; J. Geier, S. Xu, (2004), “Modelling of Radionuclide Transport by Groundwater Motion in Fractured Bedrock for Performance Assessment Purposes”, SKI technical report, in press.

Xu, S.; A. Wörman (1999), Implications of Sorption Kinetics to Radionuclide Migration in Fractured Rock, Water Resources Research, 35(11), 3429-3440.

Xu, S.; A. Wörman (1998), Statistical Patterns of Geochemistry in Crystalline Rock and Effect of Sorption Kinetics on Radionuclide Migration, SKI Report 98:41, Stockholm, Sweden, ISSN 1104-1374.

Xu, S.; A. Wörman, Dverstorp, B., (2001), “Heterogeneous matrix diffusion in crystalline rock – Implications for geosphere retardation of migrating radionuclides”, Journal of Contaminant Hydrology, FEB 2001: 47(2-4) 365-378.

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