A Review on Uncertainty Analysis Methodologies for the Safety Case of a HLW Repository

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1. Introduction

The aim of deep geological disposal of radioactive wastes is to protect humans and the environment from the hazards associated with radioactive waste over timescales up to several thousand or even a million year. Therefore, the evolution of the disposal system over long periods of time should be considered for the safe management of radioactive waste. And the uncertainties associated with the evolution of the disposal system must be appropriately considered and managed throughout a whole repository development program. In addition, the uncertainties and the potential for reducing them in subsequent development phases should be described in the safety case at each stage [1]. In this paper, elements for managing uncertainty and features of uncertainty analysis methodology are reviewed. In addition, the challenges related to uncertainty management for the safety case have been identified.

2. Uncertainty Analysis Methodologies

2.1 Uncertainty in the Safety Assessment of a Repository

The safety assessment (SA) of a waste repository is made by developing and using a computer model to simulate the important factors of a repository. The model for the repository SA includes the framework of the system model to handle input, output, Monte Carlo sampling, running of mathematical models, and analysis of results [2].

The safety assessment results of a HLW repository are inevitably subject to uncertainty due to the combined effects of data variability, erroneous measurements, wrong estimations, unrepresentative or missing data and modelling assumptions. In general, there are two kinds of uncertainties: stochastic (aleatory) and subjective (epistemic) uncertainty. A stochastic uncertainty arises from the possible evolution that could occur over long regulatory period associated with a repository, and subjective uncertainty arises from an inability to clearly characterize models and parameters required in a safety assessment.

Uncertainties in the safety assessment of a repository are generally classified as follows: 1) uncertainties associated with changes that may occur within the engineered barrier systems and the geological and surface environment over time (scenario uncertainties); 2) uncertainties arising from an incomplete knowledge or lack of understanding of the behavior of the system, as well as from the use of simplified models and assumptions (model uncertainty); 3) uncertainties associated with the values of the parameters that are used in the models for the SA (parameter uncertainties).

Fig. 1 shows the steps involved in the SA and the uncertainty analysis [2]. The first step is to sample the input parameters distributions for the SA models to generate a list of parameters for each realization. The sampled parameters are then run through the SA models to generate the performance measure such as dose to the individual. Finally, all evaluated realizations are combined to get a measure of risk to compare to the regulatory standards.

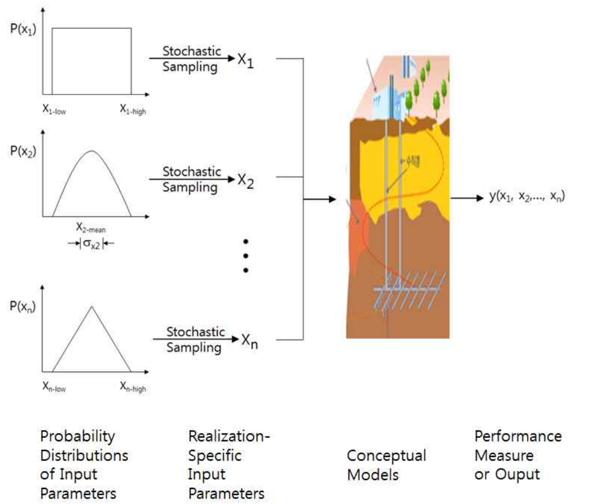

Fig. 1. Steps for the safety and the uncertainty analysis [2].

2.2 Methods for Uncertainty Analysis

According to the MeSA project [3], strategies for treating uncertainties within the safety assessment of a repository are generally falling into one or more of the following five categories: demonstrating that the uncertainty is irrelevant to safety; addressing the uncertainty explicitly; bounding the uncertainty; ruling out the uncertain event or process; using an agreed stylized approach to avoid addressing the uncertainty explicitly. There is a variety of methods and techniques for addressing uncertainties and for analyzing the sensitivity of the safety assessment outcome to specific uncertainties. These methods and techniques are not mutually exclusive, but they should be used jointly.

Four important uncertainty evaluation methods are summarized in Table I [4]. The probability-distribution approach models all the uncertainties as probability distributions. This approach may not be feasible because of the large uncertainties in the input parameters and process models. When there are not enough data to establish a distribution for an uncertain parameter, the bounding approach can be used to quantify input uncertainty, using bounds and corresponding assurance levels. Expert judgement can be used to assist in developing distribution models and transfer functions. In many cases, expert judgement may be the only practical mechanism to justify the selection of scenarios, process models, and the values of parameters. When there are insufficient data or knowledge to discriminate between several competitive models or assumptions, sensitivity analyses can be performed to identify critical uncertain parameters, so that efforts can be directed to reduce the uncertainty [4].

Table I: Uncertainty Evaluation Methods [4]

Method	Main Role
I. Probability Distribution	- Establish sub-system performance distributions (reliability analysis)
II. Bounding	- Quantify input uncertainty (bounds, assurance levels) - Provide assurance levels for results of I
III. Expert Judgement	- Quantify input uncertainty (distributional input, assurance levels) - Provide assurance levels for results of I
IV. Sensitivity Analysis	- Identify critical assumptions, parameters

2.3 Parameter Sampling

In the SA model, there are both fixed parameters and uncertain parameters represented by probability distributions. Constant values are assigned to parameters that are either well characterized or have uncertainty ranges that do not significantly affect model results. Probability distributions are assigned to parameters that are not well known or where variability is sufficient to affect model results. Selection of the particular distribution type, such as normal, uniform, or beta, can be made based on the information available for the parameter, the best fit of data to a distribution, and a reasonable assumption of the distribution type.

The probability density function (PDF) is the standard form in which uncertainties are represented in a probabilistic model. The probability density functions (PDFs) of input parameters need to be defensible especially because (i) too broad uncertainty ranges may cause risk dilution and (ii) too narrow uncertainty ranges may indicate unwarranted confidence in the parameter range, and therefore bias the results.

The PDF can be developed by several means, depending on the availability of actual parameter values. 1) If there are sufficient data, the values of the parameter can be used to generate an empirical PDF directly. 2) If data are available, but limited, the data can be combined with subjective knowledge or expert opinion to generate parameter distributions. 3) If a parameter is a combination of several other parameters whose distributions are known, they can be combined probabilistically to generate a new distribution function. This can be done formally by analytical integration or probabilistically by Monte Carlo sampling of the base distributions. 4) If data are very limited, a distribution can be generated by the "Maximum Entropy Formalism" [5].

For each realization in the SA model run, values of the parameters are sampled from the chosen distribution functions. Sampling of a single parameter is performed by generating a random number between 0 and 1 of the CDF, and then finding the value of a parameter corresponding to the CDF value. When sampling multiple parameters, a modified sampling procedure, known as Latin Hypercube Sampling (LHS), is generally substituted for purely random sampling of the CDF. The LHS procedure forces a more even distribution of samples over the range of the parameters but the method is valid for any number of sampled variables.

2.4 Risk Dilution

In general, parameter-distribution approach tend to specify wide, all-inclusive distributions when amounts of data are small. Although the use of these wide distributions tends to lead to the calculation of some realizations with large doses, wide distributions can lower the dose and risk. This situation in which an increase in the uncertainty in the values of input parameters to a model leads to a decrease in calculated risk is generally defined as risk dilution. This risk dilution has become a topic of interest to reviewers of safety cases. There are several ways in which risk dilution can arise, each of which produces slightly different effects: event timing; spatial effects; parameter correlation; and parameter distribution [6]. Risk dilution can be avoided through a systematic approach to developing a safety case and undertaking assessment calculations. Appropriate documentation is a key in providing assurance to the regulator and other stakeholders that modeling assumptions have not led to significant under-estimation of risks.

2.5 Granularity and Upscaling of Performance Models

The term "granularity" refers to a potential problem with SA codes, because the safety assessment results of a repository may be different depending on the degree of discretization [2]. Although a representative waste package is usually used in the SA of a repository, differences from package to package and differences in the package environment from place to place in the repository may affect the safety assessment results significantly. This problem is also called “upscaling,” because overall repository performance is of concern, rather than the behavior of individual waste packages [2]. This problem of granularity can be handled by increasing the number of representative waste packages, i.e., by a using multiple source term model.

2.6 Representation of Uncertainty Analysis Results

Most uncertainty analysis approaches have used Monte Carlo sampling to generate input for models and have analyzed the results to generate an approximation of risk of a repository. The typical representation of uncertainty analysis results using Monte Carlo sampling included in the safety assessment of A-KRS is shown in Fig. 2 [7]. As shown in Fig.2, the typical uncertainty analysis results consist of mean, median, 5% percentile, 95% percentile values.

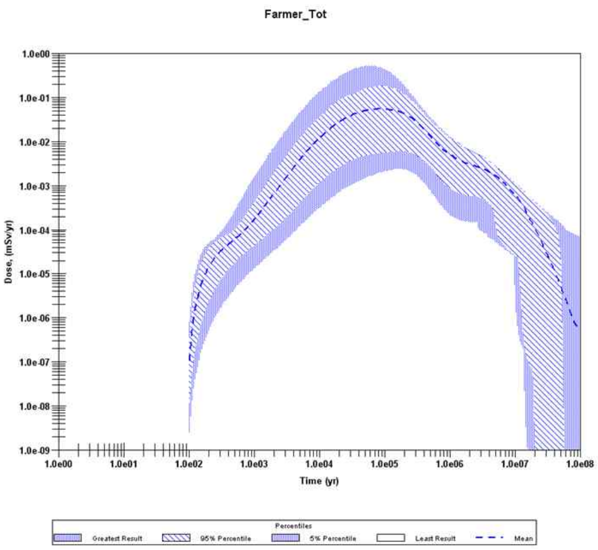

Fig. 2. Typical representation of uncertainty analysis results of A-KRS [7].

3. Conclusions

The management of uncertainty is an important element of a safety case for a radioactive waste repository. Therefore, the uncertainties associated with the evolution of the disposal system must be appropriately considered and managed throughout a repository development program. At each stage of a stepwise development program, 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.

The challenges to be resolved related to the management of uncertainty are as follows: 1) how to determine which uncertainties are matter; 2) how to make decisions when there are significant uncertainties; 3) how to demonstrate confidence in the safety case when there are still uncertainties; 4) how to regulate in the face of uncertainty; 5) how to communicate uncertainties to the public.

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