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Uncertainty and sensitivity analysis in performance assessment for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada

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ABSTRACT

Extensive work has been carried out by the U.S. Department of Energy (DOE) in the development of a proposed geologic repository at Yucca Mountain (YM), Nevada, for the disposal of high-level radioactive waste. As part of this development, a detailed performance assessment (PA) for the YM repository was completed in 2008 and supported a license application by the DOE to the U.S. Nuclear Regulatory Commission (NRC) for the construction of the YM repository. The following aspects of the 2008 YM PA are described in this presentation: (i) conceptual structure and computational organization, (ii) uncertainty and sensitivity analysis techniques in use, (iii) uncertainty and sensitivity analysis for physical processes, and (iv) uncertainty and sensitivity analysis for expected dose to the reasonably maximally exposed individual (RMEI) specified the NRC's regulations for the YM repository.

1. Introduction

Extensive work has been carried out by the U.S. Department of Energy (DOE) in the development of a proposed geologic repository at Yucca Mountain (YM), Nevada, for the disposal of high-level radioactive waste [1–6]. As part of this development, a detailed performance assessment (PA) for the YM repository was completed in 2008 [6] and supported a license application by the DOE to the U.S. Nuclear Regulatory Commission (NRC) for the construction of the YM repository [7]. This presentation provides an overview of the conceptual and computational structure of the indicated PA (hereafter referred to as the 2008 YM PA) and the roles that uncertainty analysis and sensitivity analysis play in this structure.

The following aspects of the 2008 YM PA are described in this presentation: (i) conceptual structure and computational organization (Section 2), (ii) uncertainty and sensitivity analysis techniques in use (Section 3), (iii) uncertainty and sensitivity analysis for physical processes (Section 4), and (iv) uncertainty and sensitivity analysis for expected dose to a reasonably maximally exposed individual (RMEI) specified the NRC's regulations for the YM repository (Section 5). The presentation then ends with a summary discussion (Section 6).

This presentation is based on an invited talk given at the 2010 Sensitivity Analysis of Model Output (SAMO) conference in Milan, Italy [8], and, in turn, is an adaptation of three earlier presentations given at the 2008 International High-Level Radioactive Waste Management Conference (IHLRWMC) in Las Vegas, Nevada [9–11]. The primary background reference for this presentation is a large and detailed technical report that describes the 2008 YM PA and provides references to a large body of additional reports that provide further information on the details of the 2008 YM PA and the models incorporated into this PA [6]. Selected aspects of the 2008 YM PA have also been described by the authors of this presentation in three additional conference papers [12–14] and a book chapter [15]. At present, a special issue of *Reliability Engineering & System Safety* is under development that will provide more details on uncertainty and sensitivity analysis in the 2008 YM PA than can be included in a single journal article.

2. Conceptual structure and computational organization

2.1. Regulatory background

The regulatory requirements that underlie the 2008 YM PA derive from the Energy Policy Act of 1992 [16] within which

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(i) the U.S. Environmental Protection Agency (EPA) is required to promulgate public health and safety standards for radioactive material stored or disposed of in the YM repository, (ii) the NRC is required to incorporate the EPA standards into licensing standards for the YM repository, and (iii) the DOE is required to show compliance with the NRC standards. The resulting regulatory requirements for the YM repository have two primary sources from the EPA and the NRC, respectively: (i) *Public Health and Environmental Radiation Protection Standards for Yucca Mountain, NV; Final Rule* (40 CFR Part 197) [17] and (ii) *Disposal of High-Level Radioactive Wastes in a Proposed Geologic Repository at Yucca Mountain, Nevada; Final Rule* (10 CFR Parts 2, 19, 20, etc.) [18]. The NRC also published the *Yucca Mountain Review Plan; Final Report* (YMRP) [19] to guide assessing compliance with 10 CFR Parts 2, 19, 20, etc. In turn, the DOE must carry out a PA for the YM repository that satisfies the requirements specified in the preceding documents.

The initial EPA standard [17] specified requirements that the YM repository was to satisfy for the first 10^4 yr after its closure. In a subsequent suit [20], it was ruled that the EPA did not follow guidance in a National Academy of Science (NAS) study [21] as mandated in the Energy Policy Act of 1992. In particular, it was ruled that the EPA had failed to follow guidance that the regulatory period for the YM repository should extend over the period of geologic stability at the repository site, which was suggested to be 10^6 yr. As a result, the initial standard [17] for the YM repository was remanded to the EPA for revision.

In response, the EPA published 40 CFR Part 197, *Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada; Proposed Rule*, which contained proposed revisions to the standards for the YM repository [22]. Consistent with the EPA's proposed revisions, the NRC published 10 CFR Part 63, *Implementation of a Dose Standard After 10,000 Years* [23]. The EPA's and NRC's proposals in response to the remand left most of the requirements for the first 10^4 yr after repository closure unchanged. However, new conditions were proposed for the time interval from 10^4 yr through the period of geologic stability.

The overall structure of the 2008 YM PA derives from the individual protection standard specified by the EPA and the NRC in the revised standards [22,23]. Specifically, the following standard is specified by the NRC ([23], p. 53319):

> § 63.311 Individual protection standard after permanent closure. (a) DOE must demonstrate, using performance assessment, that there is a reasonable expectation that the reasonably maximally exposed individual receives no more than the following annual dose from releases from the undisturbed Yucca Mountain disposal system: (1) 0.15 mSv (15 mrem) for 10,000 years following disposal; and (2) 3.5 mSv (350 mrem) after 10,000 years, but within the period of geologic stability. (b) DOE's performance assessment must include all potential environmental pathways of radionuclide transport and exposure. (NRC1).

Except for minor differences in wording, the preceding standard is the same as the proposed standard specified by the EPA ([22], p. 49063).

In turn, the NRC gives the following guidance on implementing the preceding individual protection standard ([23], p. 53319):

> § 63.303 Implementation of Subpart L. (a) Compliance is based upon the arithmetic mean of the projected doses from DOE's performance assessments for the period within 10,000 years after disposal for: (1) § 63.311(a)(1); and (2) §§ 63.321(b)(1) and 63.331, if performance assessment is used to demonstrate compliance with either or both of these sections. (b) Compliance is based upon the median of the projected doses from DOE's performance assessments for the period after 10,000 years of disposal and through the period of geologic stability for: (1) § 63.311(a)(2); and (2) § 63.321(b)(2), if performance assessment is used to demonstrate compliance. (NRC2)

Again, the preceding is the same as the corresponding guidance given by the EPA ([22], p. 49063).

As indicated in (NRC1) and (NRC2), the NRC expects the determination of mean and median dose to the reasonably maximally exposed individual (RMEI) to be based on a detailed PA. This expectation is further emphasized by the following statement in the YMRP ([19], p. 2.2-1):

> Risk-Informed Review Process for Performance Assessment—The performance assessment quantifies repository performance, as a means of demonstrating compliance with the postclosure performance objectives at 10 CFR 63.113. The U.S. Department of Energy performance assessment is a systematic analysis that answers the triplet risk questions: what can happen; how likely is it to happen; and what are the consequences. (NRC3)

For convenience, the preceding questions can be represented by Q1, "What can happen?", Q2, "How likely is it to happen?", and Q3, "What are the consequences if it does happen?". The preceding questions provide the intuitive basis for the Kaplan/Garrick ordered triple representation for risk:

$$(\mathcal{S}_i, pS_i, \mathbf{cS}_i), \quad i = 1,2,\ldots,nS, \tag{1}$$

where (i) $\mathcal{S}_i$ is a set of similar occurrences (i.e., the answer to Q1), (ii) pS_i is the probability of $\mathcal{S}_i$ (i.e., the answer to Q2), and (iii) $\mathbf{cS}_i$ is a vector of consequences associated with $\mathcal{S}_i$ (i.e., the answer to Q3) [24]. Further, the $\mathcal{S}_i$ must be disjoint (i.e., $\mathcal{S}_i \cap \mathcal{S}_j = \emptyset$ for $i \neq j$); each $\mathcal{S}_i$ must be sufficiently homogeneous to allow use of a single representative consequence vector $\mathbf{cS}_i$; and $\cup_i \mathcal{S}_i$ must contain all risk significant occurrences for the facility under consideration.

In addition, there is a fourth basic question that underlies the 2008 YM PA and, indeed, all complete PAs: Q4, "What is the uncertainty in the answers to the initial three questions?". The importance of answering this fourth question is emphasized in a number of statements by the NRC. For example:

> For such long-term performance, what is required is reasonable expectation, making allowance for the time period, hazards, and uncertainties involved, that the outcome will conform with the objectives for postclosure performance for the geologic repository. Demonstrating compliance will involve the use of complex predictive models that are supported by limited data from field and laboratory tests, site-specific monitoring, and natural analog studies that may be supplemented with prevalent expert judgment. Compliance demonstrations should not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence. The performance assessments and analyses should focus upon the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values ([18], p. 55804). (NRC4)

> Once again, although the criteria may be written in unqualified terms, the demonstration of compliance must take uncertainties and gaps in knowledge into account so that the Commission can make the specified finding with respect to paragraph (a)(2) of § 63.31 ([18], p. 55804). (NRC5)

Both the preceding statements clearly indicate that a reasonable treatment of uncertainty should be a fundamental part of a PA used to support a licensing application for the YM repository.