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Conceptual structure and computational organization of the 2008 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. This presentation describes the overall conceptual structure and computational organization of the 2008 performance assessment (PA) for the proposed YM repository carried out by the DOE in support of a licensing application to the U.S. Nuclear Regulatory Commission (NRC). The following topics are addressed: (i) regulatory background, (ii) the three basic entities underlying a PA, (iii) determination of expected, mean and median dose to the reasonably maximally exposed individual (RMEI) specified in the NRC regulations for the YM repository, (iv) the relationship between probability, sets and scenario classes, (v) scenario classes and the characterization of aleatory uncertainty, (vi) scenario classes and the determination of expected dose to the RMEI, (vii) analysis decomposition, (viii) disjoint and nondisjoint scenario classes, (ix) scenario classes and the NRC's YM review plan, (x) characterization of epistemic uncertainty, and (xi) adequacy of Latin hypercube sample size used in the propagation of epistemic uncertainty. This article is part of a special issue of *Reliability Engineering and System Safety* devoted to the 2008 YM PA and is intended as an introduction to following articles in the issue that provide additional analysis details and specific analysis results.

1. Introduction

The appropriate disposal of radioactive waste from research, military and commercial activities is a challenge of national and international importance [1–14]. As part of the solution to this challenge, 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 [15–20]. The development of the YM repository is the most extensive radioactive waste disposal project ever undertaken in the United States. The following presentation is adapted from Section J.4 of Ref. [20] and provides a description of the conceptual structure and computational organization of the 2008 performance assessment (PA) for the proposed YM repository.

The following topics are considered: (i) regulatory background (Section 2), (ii) the three basic entities underlying a PA (Section 3), (iii) determination of expected, mean and median dose to the reasonably maximally exposed individual (RMEI) specified in the NRC regulations for the YM repository (Section 4), (iv) the relationship between probability, sets and scenario classes (Section 5), (v) scenario classes and the characterization of aleatory uncertainty (Section 6), (vi) scenario classes and the determination of expected dose to the RMEI (Section 7), (vii) analysis decomposition (Section 8), (viii) disjoint and nondisjoint scenario classes (Section 9), (ix) scenario classes and the NRC's YM review plan (Section 10), (x) characterization of epistemic uncertainty (Section 11), and (xi) adequacy of Latin hypercube sample size used in the propagation of epistemic uncertainty (Section 12). The presentation then ends with a summary concluding discussion (Section 13). In addition, two appendices present descriptions of uncertain analysis inputs and results considered in the 2008 YM PA.

The present article is part of a special issue of *Reliability Engineering and System Safety* devoted to the 2008 YM PA and is intended as an introduction to following articles in the issue that provide additional analysis details and specific analysis results [21–32]. In addition, a sequence of preceding articles provide historical background on the development and evolution of PA procedures for the proposed YM repository [33–42]. Parts of the present article are lightly edited adaptations of material contained in a previous summary article [43] on the 2008 YM PA based on Appendices J and K of Ref. [20].

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2. Regulatory background

As mandated in the Energy Policy Act of 1992 [44], 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; the U.S. Nuclear Regulatory Commission (NRC) is required to incorporate the EPA standards into licensing standards for the YM repository; and the DOE is required to show compliance with the NRC standards. The regulatory requirements for the YM repository that resulted from these mandates have two primary sources: (i) *Public Health and Environmental Radiation Protection Standards for Yucca Mountain, NV; Final Rule* (40 CFR Part 197) [45], which has been promulgated by the EPA, 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.) [46], which has been promulgated by the NRC. In turn, the DOE is required to carry out a PA for the YM repository that satisfies the requirements specified in the preceding documents. In addition, the NRC has published the *Yucca Mountain Review Plan*; *Final Report* (YMRP) [47] to guide assessing compliance with 10 CFR Parts 2, 19, 20, etc.

The EPA and NRC standards promulgated in the final rules have developed over time, and PA for the YM repository has evolved in concert with changes to the rules [33]. The initial EPA standard indicated above specified conditions that the YM repository was required to satisfy for the first 10^4 yr after its closure. In a subsequent suit [48], it was ruled that the EPA did not follow guidance in a National Academy of Science (NAS) study [49] as mandated by Congress in the Energy Policy Act of 1992. In particular, it was ruled that the EPA had failed to follow the guidance in the NAS study that the regulatory period for the YM repository should extend over the period of geologic stability at the facility site, which was suggested to be 10^6 yr. As a result, the initial regulation for the YM facility was remanded to the EPA for revision.

In response to this remand, the EPA published 40 CFR Part 197, *Public Health and Environmental Radiation Protection Standards for Yucca Mountain, Nevada*; *Proposed Rule* [50], which contained proposed revisions to the standards for the YM repository. Consistent with the EPA's proposed revisions, the NRC published proposed 10 CFR Part 63, *Implementation of a Dose Standard After 10,000 Years* [51]. 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 proposed rules at the time that this PA was initiated. Specifically, the following standard is specified by the NRC ([51], p. 53319):

> Section 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 ([50], p. 49063).

In turn, the NRC gives the following guidance on implementing the preceding individual protection standard ([51], p. 53319):

> Section 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) Section 63.311(a)(1); and (2) Sections 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) Section 63.311(a)(2); and (2) Section 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 ([50], 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 ([47], 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:

$$(\mathcal{S}_i, pS_i, \mathbf{cS}_i), \quad i = 1, 2, \ldots, nS, \tag{2.1}$$

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) [52]. Further, the $\mathcal{S}_i$ must be disjoint (i.e., $\mathcal{S}_i \cap \mathcal{S}_i = \varnothing$ 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 YM 2008 PA and, indeed, all complete performance assessments: (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