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Uncertainty and sensitivity analysis in performance assessment for the proposed repository for high-level radioactive waste 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, an extensive performance assessment (PA) for the YM repository was completed in 2008 [1] and supported a license application by the DOE to the U.S. Nuclear Regulatory Commission (NRC) for the construction of the YM repository [2]. 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.

Aleatory Uncertainty, Epistemic Uncertainty, Performance Assessment, Radioactive waste disposal, Sensitivity Analysis, Yucca Mountain

1. Main text

The 2008 YM PA is underlain by three basic entities or components: EN1, a probability space $(\mathcal{A}, \mathbb{A}, p_A)$ that characterizes aleatory uncertainty; EN2, a function f that estimates consequences for individual elements $\mathbf{a}$ of the sample space $\mathcal{A}$ for aleatory uncertainty; and EN3, a probability space $(\mathcal{E}, \mathbb{E}, p_E)$ that characterizes epistemic uncertainty [3]. A recognition and understanding of these three basic entities makes it possible to understand the conceptual and computational structure of the 2008 YM PA without having basic concepts obscured by fine details of the analysis and leads to an analysis structure that results in insightful uncertainty and sensitivity analyses.

The probability space $(\mathcal{A}, \mathbb{A}, p_A)$ corresponding to the entity EN1 provides a complete categorization and probabilistic characterization of the possible futures that are incorporated into the 2008 YM PA. Each element $\mathbf{a}$ of the sample space $\mathcal{A}$ for aleatory uncertainty is a vector defining the properties of one possible sequence of future occurrences at the YM repository. The occurrences incorporated into the definition of $\mathbf{a}$ include early failures of

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waste packages and drip shields, igneous events involving intrusion of the repository and possibly surface eruptions, and seismic events involving ground motion and fault displacement ([1], App. J). These occurrences were identified for inclusion in the 2008 YM PA through an extensive review process [4; 5]. Probability distributions characterize the perceived randomness in the occurrence of the individual elements of $\mathbf{a}$ and, in essence, lead to the full definition of the probability space $(\mathcal{A}, \mathbb{A}, p_A)$.

The probability space $(\mathcal{E}, \mathbb{E}, p_E)$ corresponding to the entity EN3 provides a complete categorization and probabilistic characterization of the epistemically uncertain quantities that are incorporated into the 2008 YM PA. Each element $\mathbf{e}$ of the sample space $\mathcal{E}$ for epistemic uncertainty is a vector defining one possible set of values for the 392 epistemically uncertain quantities incorporated into the 2008 YM PA. Included in the elements of $\mathbf{e}$ are (i) physical quantities such as permeabilities and sorption coefficients, (ii) designators for alternative models, and (iii) parameters used in the characterization of aleatory uncertainty ([1], Table K3-3). In more detail, $\mathbf{e}$ has the form $\mathbf{e} = [\mathbf{e}_A, \mathbf{e}_M]$, where $\mathbf{e}_A$ and $\mathbf{e}_M$ are vectors of epistemically uncertain quantities involved in the characterization of aleatory uncertainty and the modeling of physical processes, respectively. Probability distributions characterize the epistemic uncertainty in the individual elements of $\mathbf{e}$ and, in essence, lead to the full definition of the probability space $(\mathcal{E}, \mathbb{E}, p_E)$.

The function f corresponding to the entity EN2 estimates the evolution through time of the YM repository system conditional on specific elements $\mathbf{a}$ and $\mathbf{e} = [\mathbf{e}_A, \mathbf{e}_M]$ of the sample spaces for aleatory uncertainty and epistemic uncertainty. Thus, a more appropriate representation for f is $\mathbf{f}(\tau|\mathbf{a}, \mathbf{e}_M)$, where (i) τ corresponds to time, (ii) the dependence of f on $\mathbf{a}$ and $\mathbf{e}_M$ is made explicit, and (iii) a vector notation is used for f to emphasize that large numbers of analysis outcomes are being estimated. In the 2008 YM PA, the function $\mathbf{f}(\tau|\mathbf{a}, \mathbf{e}_M)$ is quite involved and corresponds to the linkage of a sequence of complex computer models representing a variety of physical processes (e.g., unsaturated and saturated fluid flow, heat flow, waste package degradation, evolution of chemical conditions, radionuclide transport, human radiation exposure, …). Further, the various submodels that collectively constitute f change depending on the specific occurrences associated with $\mathbf{a}$. Descriptions of f and its associated submodels are available in Ref. [1] and in the more detailed model-specific technical reports cited in Ref. [1].

Uncertainty analysis in the 2008 YM PA involved separate and combined propagations of aleatory and epistemic uncertainty. Formally, this involved integrations of f over the sample spaces $\mathcal{A}$ and $\mathcal{E}$ for aleatory and epistemic uncertainty, respectively. Further, the analyses and associated integrations underlying the 2008 YM PA were decomposed into the consideration of seven distinct (but not necessarily disjoint) subsets of $\mathcal{A}$ (i.e., scenario classes): undisturbed conditions, early waste package failure, early drip shield failure, igneous intrusion, igneous eruption, seismic ground motion, and seismic fault displacement. Appropriate and numerically efficient integration techniques based on either quadrature or random sampling procedures were then used in the propagation of aleatory uncertainty for the indicated scenario classes ([1], App. J). Epistemic uncertainty was propagated with a Latin hypercube sample (LHS) of size 300 from the 392 epistemically uncertain elements of $\mathbf{e}$ [6; 7]. The same LHS was used for all scenario classes, which made possible the combining of epistemic uncertainty results across scenario classes. The separate and combined propagations of aleatory and epistemic uncertainty lead to a variety of uncertainty representations, including (i) epistemic uncertainty conditional on specific futures $\mathbf{a}$, (ii) epistemic uncertainty in distributions deriving from aleatory uncertainty, (iii) epistemic uncertainty in time-dependent expected values deriving from aleatory uncertainty, and (iv) time-dependent expected values deriving from both aleatory and epistemic uncertainty ([1], App. J).

The mapping between analysis inputs and results associated with the LHS used to propagate epistemic uncertainty also provided the basis for the application of a variety of sensitivity analysis procedures [8]. Owing to their generally robust performance, the primary sensitivity analysis procedures used in the 2008 YM PA involved the use of scatterplots, partial rank correlation coefficients, and stepwise rank regression analyses. To fully understand the overall results obtained in the 2008 YM PA, sensitivity analyses were carried out for several hundred time-dependent results, including repository conditions, waste package degradation, radionuclide release and movement, and human radiation exposure through a variety of exposure pathways ([1], App. K)

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