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Uncertainty and sensitivity analysis for the nominal scenario class in 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. In support of this development and an associated license application to the U.S. Nuclear Regulatory Commission (NRC), the DOE completed an extensive performance assessment (PA) for the proposed YM repository in 2008. This presentation describes uncertainty and sensitivity analysis results for the nominal scenario class (i.e., for undisturbed conditions) obtained in the 2008 YM PA. The following topics are addressed: (i) uncertainty and sensitivity analysis procedures, (ii) drip shield and waste package failure, (iii) engineered barrier system conditions, (iv) radionuclide release results for the engineered barrier system, unsaturated zone, and saturated zone, and (v) dose to the reasonably maximally exposed individual specified in the NRC regulations for the YM repository. The present article is part of a special issue of *Reliability Engineering and System Safety* devoted to the 2008 YM PA; additional articles in the issue describe other aspects of the 2008 YM PA.

1. Introduction

Uncertainty and sensitivity analysis are fundamental components of the 2008 performance assessment (PA) conducted by the U.S. Department of Energy (DOE) for a proposed high-level radioactive waste repository at Yucca Mountain (YM), Nevada [1,2]. The following presentation describes uncertainty and sensitivity analysis results obtained for the nominal scenario class [3] in the 2008 YM PA. Additional presentations describe uncertainty and sensitivity analysis results obtained in the 2008 YM PA for early failure scenario classes [4,5], igneous scenario classes [6,7], seismic scenario classes [8,9], and all scenario classes collectively [10].

The following topics are considered in this presentation: uncertainty and sensitivity analysis procedures (Section 2), drip shield (DS) and waste package (WP) failure (Section 3), engineered barrier system (EBS) conditions (Section 4), radionuclide release results for the EBS, unsaturated zone (UZ) and saturated zone (SZ) (Section 5), and dose to the reasonably maximally exposed individual (RMEI) (Section 6). The presentation then ends with a summary discussion (Section 7).

2. Uncertainty and sensitivity analysis procedures

Conceptually, the 2008 YM PA can be represented by

$$\mathbf{y} = \mathbf{f}(\mathbf{e}), \tag{1}$$

where

$$\mathbf{e} = [\mathbf{e}_A,\ \mathbf{e}_M] = [e_1,\ e_2,\ \ldots,\ e_{nE}] \tag{2}$$

is a vector of epistemically uncertain analysis inputs,

$$\mathbf{y} = [y_1,\ y_2,\ \ldots,\ y_{nY}] \tag{3}$$

is a vector of epistemically uncertain analysis results, and the function $\mathbf{f}$ denotes the suite of models that constitute the modeling

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system used in the 2008 YM PA. The elements of $\mathbf{e}$ are listed and defined in Appendix B of Ref. [2]; further, additional information on the elements of $\mathbf{e}$ and extensive background references are given in Table K3-3 of Ref. [1]. As a reminder, the vectors $\mathbf{e}_A$ and $\mathbf{e}_M$ contain variables that affect the characterization of aleatory uncertainty and the modeling of physical processes, respectively (see Section 3, Ref. [2]). Selected elements of the vector $\mathbf{y}$ are listed in Appendix A of Ref. [2]. The function $\mathbf{f}$ is very complex and corresponds to the entire modeling process used to represent physical processes in the 2008 YM PA. A high-level description of $\mathbf{f}$ and sources of more detailed information are given in Ref. [11] and in Section 6 of Ref. [1]. In addition, an extensive description of the development process that led to the models that constitute the function $\mathbf{f}$ is given in Refs. [12–21]. The overall structure of $\mathbf{f}$ for the nominal scenario class is indicated in Fig. 2 of Ref. [11]. Further, $\mathbf{f}$ has a similar structure for the early failure, igneous intrusive and seismic scenario classes and a very different structure for the igneous eruptive scenario class as indicated in Fig. 1 of Ref. [6].

The 2008 YM PA employs uncertainty and sensitivity analysis procedures based on a mapping between analysis inputs and analysis results generated with use of Latin hypercube sampling [22,23]. As discussed in Section 12 of Ref. [2], a Latin hypercube sample (LHS)

$$\mathbf{e}_i = [\mathbf{e}_{Ai},\ \mathbf{e}_{Mi}],\ \ i = 1,\ 2,\ \ldots,\ nLHS, \tag{4}$$

is generated from the epistemically uncertain analysis inputs in consistency with the probability space $(\mathcal{E},\ \mathbb{E},\ p_E)$ used to characterize epistemic uncertainty (see Eq. (3.3) of Ref. [2] and associated discussion). In the computational implementation of the 2008 YM PA, the probability space $(\mathcal{E},\ \mathbb{E},\ p_E)$ is, in effect, defined by assigning a probability distribution D_j to each element e_j of $\mathbf{e}$.

The 2008 YM PA analysis uses an LHS of size $nLHS = 300$ from the elements $\mathbf{e}$ of $\mathcal{E}$. Further, as discussed in Section 12 of Ref. [2], this sample is replicated $nR = 3$ times to test for the stability of analysis results.

Evaluation of $\mathbf{f}$ for each element $\mathbf{e}_i = [\mathbf{e}_{Ai},\ \mathbf{e}_{Mi}]$ of the LHS in Eq. (4) generates a mapping

$$\mathbf{y}_i = \mathbf{f}(\mathbf{e}_i), i = 1, 2, \ldots, nLHS, \tag{5}$$

from epistemically uncertain inputs contained in $\mathbf{e}_i$ to epistemically uncertain results contained in $\mathbf{y}_i$. Once generated, this mapping forms the basis for both uncertainty analysis and sensitivity analysis. Specifically, the weights associated with the individual LHS elements (i.e., $1/nLHS$) permit the construction of distributions for elements of $\mathbf{y}$ that characterize epistemic uncertainty, and the mapping itself can be explored with a variety of sensitivity analysis procedures to determine the effects of individual elements of $\mathbf{e}$ on elements of $\mathbf{y}$ [24,25].

The primary sensitivity analysis procedures used in the 2008 YM PA involve the determination and presentation of partial rank correlation coefficients (PRCCs), stepwise rank regression analyses, and scatterplots.

Partial rank correlation coefficients (PRCCs) provide a measure of the strength of the monotonic relationship between an independent variable e (i.e., an element of $\mathbf{e}$) and a dependent variable y (i.e., an element of $\mathbf{y}$) after a correction has been made to remove the monotonic effects of the other independent variables in the analysis (i.e., the elements of $\mathbf{e}$ other than e). Most of the elements of $\mathbf{y}$ under consideration in the 2008 YM PA are functions of time (e.g., see Fig. 1a). For such variables, the presentation of PRCCs as functions of time provides an informative display of sensitivity analysis results (e.g., see Fig. 1b).

Percolation bin 3 is referred to the caption in Fig. 1. To simplify representation of spatial variability in thermal-hydrologic conditions over the repository footprint ([11], Section 3.4), WPs are grouped into 5 percolation bins (Fig. 2). Each percolation bin corresponds to a different interval of percolation rates above the repository footprint (i.e., 0.15–0.82 mm/yr for bin 1, 0.82–4.55 mm/yr for bin 2, 4.55–14.06 mm/yr for bin 3, 14.06–26.16 mm/yr for bin 4, and 26.16–36.19 mm/yr for bin 5 as described in conjunction with Table 6-26 of Ref. [26]). Percolation bin 3 contains 3285 commercial spent nuclear fuel (CSNF) WPs and 1366 codisposed spent nuclear fuel (CDSP) WPs (approximately 40% of the 11,629 WPs in the repository), which is more WPs than in any one of the other four percolation bins. For this reason, percolation bin 3 is often selected for use in the illustration of analysis results that are conditional on individual percolation bins.

As indicated by the name, PRCCs involve the analysis of rank-transformed data. With this approach, the values for variables are replaced with their ranks and then the PRCCs are calculated with these ranks rather than with the original values for the variables. Specifically, the smallest value of a variable is given a rank of 1; the next largest value is given a rank of 2; equal observations are assigned the average of what their ranks would have been if they had not been equal; and so on up to the largest value, which is given a rank equal to the number of sample elements in use (i.e., $nLHS = 300$ in the 2008 YM PA). The effect of the rank transformation is to transform monotonic relationships into linear relationships. Further, the rank transform tends to reduce the skewing effects of outliers, which permits analyses to represent the general relationships between the inputs and the output of interest. Although no variable transformation is universally successful in improving the resolution of a sensitivity analysis in the presence of nonlinear relationships, the rank transformation has been found to be a broadly effective and useful means of enhancing the insights obtained in sensitivity analyses based on partial correlation and also in sensitivity analyses based on stepwise regression.

In the example in Fig. 1, the time-dependent results for the variable under consideration (i.e., *NCSFL*, number of failed CSNF WPs in percolation bin 3) are presented in Fig. 1a and the corresponding PRCCs are presented in Fig. 1b. Fig. 1a contains 300 time-dependent values for *NCSFL*. Thus, at each time there are 300 values for *NCSFL* for which a PRCC is calculated for each element e of $\mathbf{e}$. In the calculation of PRCCs for a particular dependent variable y that is not influenced by all elements of $\mathbf{e}$, such as release of a particular radionuclide from the EBS, the elements of $\mathbf{e}$ that are known to be unrelated to the determination of the dependent variable y are excluded from this calculation. The exclusion of these elements reduces the occurrence of spurious correlations in the PRCC calculation results. Then, the PRCCs are plotted above the time at which they were calculated and connected for each independent variable e to show the effect of e on the dependent variable (i.e., *NCSFL* in this example) as a function of time. To limit the number of time-dependent PRCC curves in a given plot frame, the PRCC plots constructed in the 2008 YM PA only show PRCC curves for the six variables with the largest PRCCs in absolute value over the time interval under consideration. Further, plots are only shown for variables whose PRCCs exceed 0.3 in absolute value at some point in time. Variables with PRCCs less than 0.3 in absolute value have only a limited monotonic effect on the output variable under consideration. In the legend of a figure showing PRCCs, the variables are listed in decreasing order of PRCC (i.e., the variable having the largest PRCC in absolute value over the time interval under consideration is listed first).

Values of PRCCs fall in the interval $[-1, 1]$, with (i) positive PRCCs indicating that two variables tend to increase and decrease together (i.e., the independent variable has a positive effect on the dependent variable), (ii) negative PRCCs indicating that two variables tend to move in opposite directions (i.e., the independent variable has a negative effect on the dependent variable), and (iii) the absolute value of a PRCC indicating the strength of the