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Expected dose and associated uncertainty and sensitivity analysis results for all scenario classes 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. The conceptual structure and organization of the 2008 YM PA is based on decomposing the analysis into the following scenario classes: nominal, early waste package failure, early drip shield failure, igneous intrusive, igneous eruptive, seismic ground motion, and seismic fault displacement. This presentation describes how results obtained for the individual scenario classes are brought together in the determination of expected dose to the reasonably maximally exposed individual (RMEI) specified by the NRC in the regulatory requirements for the YM repository and presents associated uncertainty and sensitivity analysis results. The following topics are addressed: (i) determination of expected dose to the RMEI from all scenario classes, (ii) expected dose and uncertainty in expected dose to the RMEI for 0 to 20,000 yr, (iii) expected dose and uncertainty in expected dose to the RMEI from for 0 to 10^6 yr, (iv) justification for the decomposition procedure used to estimate expected dose to the RMEI from all scenario classes, and (v) effectiveness of individual barrier systems in reducing releases from the repository and thus dose to the RMEI. 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

The U.S. Nuclear Regulatory Commission (NRC) regulations for a high-level radioactive waste (HLW) repository at Yucca Mountain (YM), Nevada, require that the U.S. Department of Energy (DOE) demonstrate compliance with three separate and distinct radiation protection standards [1,2]: (i) Individual Protection Standard after Permanent Closure (10 CFR 63.311), which is based on the required characteristics of the reasonably maximally exposed individual (RMEI) as described in 10 CFR 63.312, (ii) Individual Protection Standard for Human Intrusion (10 CFR 63.321), which is based on the Human Intrusion Scenario described in 10 CFR 63.322, and (iii) Standards for Protection of Ground Water (10 CFR 63.331), which are based on the representative ground water volume specified in 10 CFR 63.332.

This presentation summarizes results of analyses performed by the DOE as part of the 2008 YM performance assessment (PA) to assess compliance with the Individual Protection Standard after Permanent Closure. Compliance with this standard is demonstrated in part by estimation of the expected dose to the RMEI specified by the NRC in the regulatory requirements for the proposed YM repository ([1; 2]; [3], Section 2; [4]). Summaries of the analyses performed in the 2008 YM PA to assess compliance with the Individual Protection Standard for Human Intrusion and the Standards for Protection of Ground Water are presented in Refs. [5,6], respectively.

The conceptual structure and organization of the 2008 YM PA are based on decomposing the analysis into the following scenario classes [3]: nominal [7,8], early waste package (WP) failure [9,10], early drip shield (DS) failure [9,10], igneous intrusive [11,12], igneous eruptive [11,12], seismic ground motion [13–15], and seismic fault displacement [13,15]. This presentation describes how results obtained for the individual scenario classes are brought together in the determination of expected dose to the RMEI and presents associated uncertainty and sensitivity analysis results.

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The following topics are considered: the determination of expected dose to the RMEI from all scenario classes (Section 2), expected dose and uncertainty in expected dose to the RMEI for 0 to 20,000 yr (Section 3), expected dose and uncertainty in expected dose to the RMEI from for 0 to 10^6 yr (Section 4), justification for the decomposition procedure used to estimate expected dose to the RMEI from all scenario classes (Section 5), and effectiveness of individual barrier systems in reducing releases from the repository and thus dose to the RMEI (Section 6). The presentation then ends with a concluding summary discussion (Section 7).

2. Determination of expected dose from all scenario classes

As described in Section 7 of Ref. [3], the 2008 YM PA assumes that expected dose to the RMEI at time τ from aleatory uncertainty can be approximated by

$$\overline{D}(\tau|\mathbf{e}) \cong D_N(\tau|\mathbf{a}_N,\mathbf{e}) + \sum_{C\in\mathcal{SC}} \overline{D}_C(\tau|\mathbf{e}) \tag{2.1}$$

conditional on the element $\mathbf{e}=[\mathbf{e}_A, \mathbf{e}_M]$ of the sample space $\mathcal{E}$ for epistemic uncertainty (see Section 3 and App. B of Ref. [3]), where

$$D_N(\tau|\mathbf{a}_N,\mathbf{e}) = \text{dose to RMEI (mrem/yr) at time } \tau \text{ for nominal conditions (i.e, for the element } \mathbf{a}_N \text{ of the sample space } \mathcal{A} \text{ for aleatory uncertainty corresponding to undisturbed conditions; see Sects. 3 and 6 of Ref. [3]),} \tag{2.2}$$

$$D_C(\tau|\mathbf{a},\mathbf{e}_M) = \text{dose to RMEI (mrem/yr) at time } \tau \text{ for scenario class } C,\ C\in\mathcal{SC}=\{EW, DS, II, IE, SG, SF\}, \text{ and } \mathbf{a}\in\mathcal{A}, \tag{2.3}$$

$$\begin{aligned}\overline{D}_C(\tau|\mathbf{e}) &= \text{expected dose to RMEI (mrem/yr) at time } \tau \text{ over aleatory uncertainty for scenario class } C, C\in\mathcal{SC}\\ &= E_A[D_C(\tau|\mathbf{a},\mathbf{e}_M)|\mathbf{e}_A]\\ &= \int_{\mathcal{A}} D_C(\tau|\mathbf{a},\mathbf{e}_M)d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A,\end{aligned} \tag{2.4}$$

and N, EW, DS, II, IE, SG and SF are used, respectively, as designators for the nominal, early WP failure, early DS failure, igneous intrusion, igneous eruption, seismic ground motion and seismic fault displacement scenario class. Further, the term $d_A(\mathbf{a}|\mathbf{e}_A)$ in Eq. (2.4) is the density function associated with the probability space $(\mathcal{A}, \mathbb{A}, p_A)$ for aleatory uncertainty ([3], Section 3), and 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 ([3], Section 3 and App. B).

Summary descriptions of the models that produce $D_N(\tau|\mathbf{a}_N, \mathbf{e}_M)$ and $D_C(\tau|\mathbf{a}, \mathbf{e}_M)$, $C\in\mathcal{SC}$, are given in Ref. [16] and in Section 6 of Ref. [17], and more detailed descriptions are available in the reports cited in Refs. [16,17] and in App. B of Ref. [3]. Further, an extensive description of the development process that led to the models that produce $D_N(\tau|\mathbf{a}_N, \mathbf{e}_M)$ and $D_C(\tau|\mathbf{a}, \mathbf{e}_M)$ is given in Refs. [18–27]. The determination of $D_N(\tau|\mathbf{a}_N, \mathbf{e}_M)$ and $\overline{D}_C(\tau|\mathbf{e})$, $C\in\mathcal{SC}$, is discussed and illustrated in Refs. [7,9,11,13].

The expected (mean) dose to the RMEI at time τ from aleatory and epistemic uncertainty is approximated by

$$\overline{\overline{D}}(\tau) \cong \overline{\overline{D}}_N(\tau) + \sum_{C\in\mathcal{SC}} \overline{\overline{D}}_C(\tau) \tag{2.5}$$

as indicated in Eq. (8.3) of Ref. [3], where

$$\overline{\overline{D}}_N(\tau) = E_E[D_N(\tau|\mathbf{a}_N,\mathbf{e}_M)] = \int_{\mathcal{E}} D_N(\tau|\mathbf{a}_N,\mathbf{e}_M)d_E(\mathbf{e})\mathrm{d}E \tag{2.6}$$

and

$$\overline{\overline{D}}_C(\tau) = E_E[\overline{D}_C(\tau|\mathbf{e})] = \int_{\mathcal{E}} \overline{D}_C(\tau|\mathbf{e})d_E(\mathbf{e})\mathrm{d}E \tag{2.7}$$

for $C\in\mathcal{SC}$. Further, the term $d_E(\mathbf{e})$ in Eqs. (2.6) and (2.7) is the density function associated with the probability space $(\mathcal{E}, \mathbb{E}, p_E)$ for epistemic uncertainty ([3], Section 3). As for the results in Eqs. (2.1)–(2.4), the determination of the results in Eqs. (2.5)–(2.7) is discussed and illustrated in Refs. [7,9,11,13].

As reminder, the 2008 YM PA uses the descriptor expected dose in reference to an expected dose over aleatory uncertainty conditional on a specific realization $\mathbf{e}=[\mathbf{e}_A, \mathbf{e}_M]$ of epistemic uncertainty. Further, the descriptors expected (mean) dose and sometimes simply mean dose are used in reference to an expected dose over both aleatory uncertainty and epistemic uncertainty. See Sects. 3–8 of Ref. [3] and Section 2 of Ref. [7] for additional discussion. It is the expected (mean) dose over both aleatory uncertainty and epistemic uncertainty that is bounded in the NRC's regulations for the proposed YM repository (see Quotes (NRC6) and (NRC7) in Section 2 of Ref. [3]).

In the 2008 YM PA, $\overline{D}_N(\tau|\mathbf{e})=0$ for $0\le\tau\le 20{,}000$ yr ([7], Section 3). Further, for $0\le\tau\le 10^6$ yr, the effects of nominal processes are incorporated into the determination of $\overline{D}_{SG}(\tau|\mathbf{e})$ ([13], Section 5). As a result, $\overline{D}(\tau|\mathbf{e})$ and $\overline{\overline{D}}(\tau)$ effectively have the forms

$$\overline{D}(\tau|\mathbf{e}) \cong \sum_{C\in\mathcal{SC}} \overline{D}_C(\tau|\mathbf{e}) \text{ and } \overline{\overline{D}}(\tau) \cong \sum_{C\in\mathcal{SC}} \overline{\overline{D}}_C(\tau) \tag{2.8}$$

for both the 20,000 yr and 10^6 yr calculations.

The same Latin hypercube sample (LHS) $\mathbf{e}_i=[\mathbf{e}_{Ai}, \mathbf{e}_{Mi}]$, $i=1, 2, \ldots, nLHS=300$, is used for all scenario classes ([3], Section 11). As a result,

$$\overline{D}(\tau|\mathbf{e}_i) \cong \sum_{C\in\mathcal{SC}} \overline{D}_C(\tau|\mathbf{e}_i) \tag{2.9}$$

for $i=1, 2, \ldots, nLHS=300$ and

$$\overline{\overline{D}}(\tau) \cong \sum_{i=1}^{300} \overline{D}(\tau|\mathbf{e}_i)/300, \tag{2.10}$$

further, quantiles $Q_{Eq}[\overline{D}(\tau|\mathbf{e})]$ for $\overline{D}(\tau|\mathbf{e})$ are defined as indicated in Eq. (4.10) of Ref. [3] and are approximated by the value D such that

$$q \cong \sum_{i=1}^{300} \underline{\delta}_D[\overline{D}(\tau|\mathbf{e}_i)]/300, \tag{2.11}$$

where

$$\underline{\delta}_D[\overline{D}(\tau|\mathbf{e}_i)] = \begin{cases} 1 & \text{if } \overline{D}(\tau|\mathbf{e}_i) \le D \\ 0 & \text{otherwise.}\end{cases} \tag{2.12}$$

Specifically, $Q_{Eq}[\overline{D}(\tau|\mathbf{e})]$ is the q quantile value (e.g., 0.05, 0.5, 0.95) for $\overline{D}(\tau|\mathbf{e})$ and is equal to the value of D that most closely satisfies Eq. (2.11).

The results $\overline{D}_r(\tau|\mathbf{e}_i)$ and $\overline{\overline{D}}_r(\tau)$ for individual radioactive species designated by r can be determined in the same manner as $\overline{D}(\tau|\mathbf{e}_i)$ and $\overline{\overline{D}}(\tau)$ in Eqs. (2.9) and (2.10). Specifically,

$$\overline{D}_r(\tau|\mathbf{e}_i) \cong \sum_{C\in\mathcal{SC}} \overline{D}_{C,r}(\tau|\mathbf{e}_i) \text{ and } \overline{\overline{D}}_r(\tau) \cong \sum_{i=1}^{300} \overline{D}_r(\tau|\mathbf{e}_i)/300, \tag{2.13}$$

where $\overline{D}_{C,r}(\tau|\mathbf{e}_i)$is the expected dose to the RMEI (mrem/yr) at time τ for scenario class C, $C\in\mathcal{SC}$, and radioactive species r conditional on $\mathbf{e}_i$.

3. Expected dose for all scenario classes: 0 to 20,000 yr

The outcomes of the calculation to determine expected dose for all scenario classes (i.e., $\overline{D}(\tau|\mathbf{e}_i)$ and $Q_{Eq}[\overline{D}(\tau|\mathbf{e})]$ for $q=0.05$, 0.5 and 0.95) and associated expected (mean) dose (i.e., $\overline{\overline{D}}(\tau)$) for $0\le\tau\le 20{,}000$ yr are summarized in Fig. 1. Initial transport to the location of the RMEI takes up to 2000 yr; after the earliest possible arrival time for released radionuclides at the location of the RMEI, expected dose $\overline{D}(\tau|\mathbf{e})$ to the RMEI (i.e., *EXPDOSE*) increases monotonically with time (Fig. 1). At 10^4 yr, the value