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Expected dose for the early failure 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. This presentation describes the determination of expected dose to the reasonably maximally exposed individual (RMEI) specified in the NRC regulations for the YM repository for the early waste package (WP) failure scenario class and the early drip shield (DS) failure scenario class in the 2008 YM PA. The following topics are addressed: (i) properties of the early failure scenario classes and the determination of dose and expected dose the RMEI, (ii) expected dose and uncertainty in expected dose to the RMEI from the early WP failure scenario class, (iii) expected dose and uncertainty in expected dose to the RMEI from the early DS failure scenario class, (iv) expected dose and uncertainty in expected dose to the RMEI from the combined early WP and early DS failure scenario class with and without the inclusion of failures resulting from nominal processes, and (v) uncertainty in the occurrence of early failure scenario classes. 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

Three primary classes of disruptions are considered in the 2008 performance assessment (PA) conducted by the U.S. Department of Energy (DOE) for a proposed repository for high-level radioactive waste at Yucca Mountain (YM), Nevada: early failure events, igneous events, and seismic events [1,2]. The focus of this presentation is on early failure events. Specifically, two types of early failures are considered in the 2008 YM PA: early waste package (WP) failures and early drip shield (DS) failures. This presentation describes the determination of expected dose from early failures to the reasonably maximally exposed individual (RMEI) specified by the U.S. Nuclear Regulatory Commission (NRC) in the regulatory requirements for the YM repository ([2], Section 2; [3,4]) and presents associated uncertainty analysis results.

The following topics are considered: properties of the early failure scenario classes and the determination of dose and expected dose the RMEI (Section 2), expected dose and uncertainty in expected dose to the RMEI from the early WP failure scenario class (Section 3), expected dose and uncertainty in expected dose to the RMEI from the early DS failure scenario class (Section 4), expected dose and uncertainty in expected dose to the RMEI from the combined early WP and early DS failure scenario class with and without the inclusion of failures resulting from nominal processes (Section 5), and the uncertainty in the occurrence of early failure scenario classes (Section 6). The presentation then ends with a concluding summary discussion (Section 7).

A following presentation presents extensive uncertainty and sensitivity analyses related to the determination of dose and expected dose to the RMEI for the early failure scenario classes [5]. Additional presentations consider the nominal scenario class [6,7], igneous scenario classes [8,9], seismic scenario classes [10,11], and all scenario classes together [12].

2. Early failure scenario classes: $\mathcal{A}_E$, $\mathcal{A}_{EW}$ and $\mathcal{A}_{ED}$

The early WP failure scenario class and the early DS failure scenario class are defined by the sets

$$\mathcal{A}_{EW} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nEW \geq 1\} \quad (2.1)$$

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and

$$\mathcal{A}_{ED} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nED \geq 1\} \tag{2.2}$$

as indicated in Eqs. (6.13) and (6.14) of Ref. [2]. In the preceding, $\mathcal{A}$ is the sample space for aleatory uncertainty defined in Section 6 of Ref. [2], and nEW and nED are the number of early WP failures and early DS failures, respectively, associated with the element $\mathbf{a}$ of $\mathcal{A}$. Further, the combined early failure scenario class $\mathcal{A}_E$ is defined by

$$\mathcal{A}_E = \mathcal{A}_{EW} \cup \mathcal{A}_{ED} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nEW + nED \geq 1\}. \tag{2.3}$$

Then, $p_A(\mathcal{A}_{EW})$ is the probability of one or more early WP failures; $p_A(\mathcal{A}_{ED})$ is the probability of one or more early DS failures; and $p_A(\mathcal{A}_E)$ is the probability of one or more early failures.

The subsets $\mathcal{A}_{EW}$ and $\mathcal{A}_{ED}$ of $\mathcal{A}$ are not disjoint. For the early WP failure scenario class and the early DS failure scenario class to be disjoint from both each other and also from the scenario classes $\mathcal{A}_{II}$, $\mathcal{A}_{IE}$, $\mathcal{A}_{SG}$ and $\mathcal{A}_{SF}$ defined in Eqs. (6.15)–(6.18) of Ref. [2] requires their definitions to be based on the sets

$$\tilde{\mathcal{A}}_{EW} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A}, nEW \geq 1 \text{ and } nED = nII = nIE = nSG = nSF = 0\} \tag{2.4}$$

and

$$\tilde{\mathcal{A}}_{ED} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A}, nED \geq 1 \text{ and } nEW = nII = nIE = nSG = nSF = 0\}, \tag{2.5}$$

respectively, where (i) nII is the number of igneous intrusive events associated with $\mathbf{a}$ and (ii) nIE, nSG, and nSF are defined similarly for igneous eruptive events, seismic ground motion events and seismic fault displacement events. In turn,

$$p_A(\tilde{\mathcal{A}}_{EW}) = p_A(\mathcal{A}_{EW})p_A(\{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nED = nII = nIE = nSG = nSF = 0\}) \tag{2.6}$$

and

$$p_A(\tilde{\mathcal{A}}_{ED}) = p_A(\mathcal{A}_{ED})p_A(\{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nEW = nII = nIE = nSG = nSF = 0\}) \tag{2.7}$$

under the assumption that the occurrences of early WP failure and early DS failure are independent of both each other and also the other types of disruption under consideration. Specifically, $p_A(\tilde{\mathcal{A}}_{EW})$ is the probability that one or more early WP failures occur and also that no other disruptive events take place, and $p_A(\tilde{\mathcal{A}}_{ED})$ is the probability that one or more early DS failures occur and also that no other disruptive events take place.

When the second term in the products in Eqs. (2.6) and (2.7) is small, then $p_A(\tilde{\mathcal{A}}_{EW})$ and $p_A(\tilde{\mathcal{A}}_{ED})$ will be much smaller than $p_A(\mathcal{A}_{EW})$ and $p_A(\mathcal{A}_{ED})$. For this reason, it is the probabilities $p_A(\mathcal{A}_{EW})$ and $p_A(\mathcal{A}_{ED})$ for the scenario classes $\mathcal{A}_{EW}$ and $\mathcal{A}_{ED}$ that are usually of interest rather than the probabilities $p_A(\tilde{\mathcal{A}}_{EW})$ and $p_A(\tilde{\mathcal{A}}_{ED})$ for the more restricted (and disjoint) scenario classes $\tilde{\mathcal{A}}_{EW}$ and $\tilde{\mathcal{A}}_{ED}$. If the question is asked "What is the probability of early WP failure?", then most likely $p_A(\mathcal{A}_{EW})$ is the desired answer. Similarly, if the question is asked "What is the probability of early DS failure?", then most likely the desired answer is $p_A(\mathcal{A}_{ED})$. It is very unlikely that the desired answers are $p_A(\tilde{\mathcal{A}}_{EW})$ and $p_A(\tilde{\mathcal{A}}_{ED})$ as these probabilities provide little useful information about the likelihood of early WP and early DS failures.

No synergisms are assumed to exist between the doses that result from early WP failures and early DS failures; a justification for this assumption is provided in Section 5 of Ref. [12]. Further, as indicated in conjunction with Eq. (7.1) of Ref. [2], no synergisms are assumed to exist between doses that result from early failures and doses that result from other disruptions. As a result,

$$D_E(\tau|\mathbf{a}, \mathbf{e}_M) = D_{EW}(\tau|\mathbf{a}, \mathbf{e}_M) + D_{ED}(\tau|\mathbf{a}, \mathbf{e}_M), \tag{2.8}$$

where (i) $D_E(\tau|\mathbf{a}, \mathbf{e}_M)$=dose to RMEI (mrem/yr) at time τ resulting from early failures associated with element $\mathbf{a}$ of $\mathcal{A}_E$, (ii) $D_{EW}(\tau|\mathbf{a}, \mathbf{e}_M)$=dose to RMEI (mrem/yr) at time τ resulting from early WP failures associated with element $\mathbf{a}$ of $\mathcal{A}_E$, (iii) $D_{ED}(\tau|\mathbf{a}, \mathbf{e}_M)$=dose to RMEI (mrem/yr) at time τ resulting from early DS failures associated with element $\mathbf{a}$ of $\mathcal{A}_E$, and (iv) all results are conditional on the element $\mathbf{e}=[\mathbf{e}_A, \mathbf{e}_M]$ of the sample space $\mathcal{E}$ for epistemic uncertainty. 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 Sections 3–8 and Appendix B of Ref. [2]). If $\mathbf{a}$ involves no early WP failures (i.e., if nEW=0 or, equivalently, if $\mathbf{a} \notin \mathcal{A}_{\mathcal{E}W}$), then $D_{EW}(\tau|\mathbf{a}, \mathbf{e}_M)$=0; similarly, if $\mathbf{a}$ involves no early DS failures (i.e., if nED=0 or, equivalently, if $\mathbf{a} \notin \mathcal{A}_{ED}$), then $D_{ED}(\tau|\mathbf{a}, \mathbf{e}_M)$=0.

The overall structure of the modeling process that determines $D_E(\tau|\mathbf{a},\mathbf{e}_M)$, $D_{EW}(\tau|\mathbf{a},\mathbf{e}_M)$ and $D_{ED}(\tau|\mathbf{a},\mathbf{e}_M)$ is summarized in Fig. 2 of Ref. [13]. With two exceptions, the models summarized in Fig. 2 of Ref. [13] for the nominal scenario class are the same as those used to determine $D_E(\tau|\mathbf{a}, \mathbf{e}_M)$ for the early failure scenario classes [6]. For the early WP failure scenario class, the models for corrosion of the WP outer barrier indicated in Fig. 2 of Ref. [13] are replaced by the assumption that, for early-failed WPs, the entire WP outer barrier is failed at time 0 and does not impede water flow or radionuclide transport. For the early DS failure scenario class, the models for corrosion of the DS are replaced by the assumption that, for early-failed DSs, the entire DS surface is failed at time 0 and does not impede water flow onto the underlying WP. In addition, in the early DS failure scenario class, the models for corrosion of the WP outer barrier are replaced by the assumption that the entire outer barrier of a WP underlying an early-failed DS also fails if seepage occurs at that location. Summary descriptions of the models that produce $D_E(\tau|\mathbf{a}, \mathbf{e}_M)$, $D_{EW}(\tau|\mathbf{a}, \mathbf{e}_M)$ and $D_{ED}(\tau|\mathbf{a}, \mathbf{e}_M)$ are given in Ref. [13] and in Section 6 of Ref. [1], and more detailed descriptions are available in the reports cited in Refs. [1,13] and in Appendix B of Ref. [2]. Further, an extensive description of the development process that led to the models that produce $D_E(\tau|\mathbf{a}, \mathbf{e}_M)$, $D_{EW}(\tau|\mathbf{a}, \mathbf{e}_M)$ and $D_{ED}(\tau|\mathbf{a}, \mathbf{e}_M)$ is given in Refs. [14–23].

The expected dose $\overline{D}_E(\tau|\mathbf{e})$ to the RMEI (mrem/yr) at time τ from early failures is given by

$$\begin{aligned}\overline{D}_E(\tau|\mathbf{e}) &= \int_{\mathcal{A}_E} D_E(\tau|\mathbf{a}, \mathbf{e}_M)d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A \\ &= \int_{\mathcal{A}_E} \left[D_{EW}(\tau|\mathbf{a}, \mathbf{e}_M) + D_{ED}(\tau|\mathbf{a}, \mathbf{e}_M)\right] d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A \\ &= \int_{\mathcal{A}_E} D_{EW}(\tau|\mathbf{a}, \mathbf{e}_M)d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A + \int_{\mathcal{A}_E} D_{ED}(\tau|\mathbf{a}, \mathbf{e}_M)d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A \\ &= \overline{D}_{EW}(\tau|\mathbf{e}) + \overline{D}_{ED}(\tau|\mathbf{e}),\end{aligned} \tag{2.9}$$

where (i)

$$\begin{aligned}\overline{D}_{EW}(\tau|\mathbf{e}) &= \int_{\mathcal{A}_E} D_{EW}(\tau|\mathbf{a}, \mathbf{e}_M)d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A \\ &= \int_{\mathcal{A}_{EW}} D_{EW}(\tau|\mathbf{a}, \mathbf{e}_M)d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A\end{aligned} \tag{2.10}$$

is the expected dose to the RMEI (mrem/yr) at time τ resulting from early WP failures as previously indicated in Eq. (7.9) of Ref. [2], (ii)

$$\begin{aligned}\overline{D}_{ED}(\tau|\mathbf{e}) &= \int_{\mathcal{A}_E} D_{ED}(\tau|\mathbf{a}, \mathbf{e}_M)d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A \\ &= \int_{\mathcal{A}_{ED}} D_{ED}(\tau|\mathbf{a}, \mathbf{e}_M)d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A\end{aligned} \tag{2.11}$$

is the expected dose to the RMEI (mrem/yr) at time τ resulting from early DS failures as previously indicated in Eq. (7.10) of Ref. [2], (iii) $d_A(\mathbf{a}|\mathbf{e}_A)$ is the density function associated with the probability space $(\mathcal{A}, \mathbb{A}, p_A)$ for aleatory uncertainty ([2], Section 3), and (iv) all results are conditional on the element $\mathbf{e}=[\mathbf{e}_A, \mathbf{e}_M]$