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Expected dose for the igneous scenario classes in the 2008 performance assessment for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada

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A R T I C L E I N F O

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A B S T R A C T

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 igneous intrusive scenario class and the igneous eruptive scenario class in the 2008 YM PA. The following topics are addressed: (i) properties of the igneous scenario classes and the determination of dose and expected dose to the RMEI, (ii) expected dose and uncertainty in expected dose to the RMEI from the igneous intrusive scenario class, (iii) expected dose and uncertainty in expected dose to the RMEI from the igneous eruptive scenario class, (iv) expected dose and uncertainty in expected dose to the RMEI from the combined igneous intrusive and igneous eruptive scenario class, and (v) uncertainty in the occurrence of igneous 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 igneous events. Specifically, two types of igneous events are considered in the 2008 YM PA: igneous intrusive events and igneous eruptive events. This presentation describes the determination of expected dose from igneous events 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 igneous scenario classes and the determination of dose and expected dose to the RMEI (Section 2), expected dose and uncertainty in expected dose to the RMEI from the igneous intrusive scenario class (Section 3), expected dose and uncertainty in expected dose to the RMEI from the igneous eruptive scenario class (Section 4), expected dose and uncertainty in expected dose to the RMEI from the combined igneous intrusive and igneous eruptive scenario class (Section 5), and the uncertainty in the occurrence of igneous 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 igneous scenario classes [5]. Additional presentations consider the nominal scenario class [6,7], early failure scenario classes [8,9], seismic scenario classes [10,11], and all scenario classes together [12].

2. Igneous scenario classes: $\mathcal{A}_I$, $\mathcal{A}_{II}$ and $\mathcal{A}_{IE}$

The igneous intrusive scenario class and the igneous eruptive scenario class are defined by the following sets:

$$\mathcal{A}_{II} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nII \geq 1\} \tag{2.1}$$

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and

$$\mathcal{A}_{IE} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nIE \ge 1\} \tag{2.2}$$

as indicated in Eqs. (6.15) and (6.16) of Ref. [2]. In the preceding, $\mathcal{A}$ is the sample space for aleatory uncertainty defined in Section 6 of Ref. [2], and nII and nIE are the number of igneous intrusive events and igneous eruptive events, respectively, associated with the element $\mathbf{a}$ of $\mathcal{A}$. Further, the igneous scenario class $\mathcal{A}_I$ is defined by

$$\mathcal{A}_I = \mathcal{A}_{II} \cup \mathcal{A}_{IE} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nII \ge 1\} = \mathcal{A}_{II} \tag{2.3}$$

as indicated in Eq. (6.11) of Ref. [2]. The equality $\mathcal{A}_I = \mathcal{A}_{II}$ results because the occurrence of an igneous intrusive event is a necessary, but not sufficient, condition for the occurrence of an igneous eruptive event in the 2008 YM PA. In turn, $p_A(\mathcal{A}_I) = p_A(\mathcal{A}_{II})$ is the probability of one or more igneous intrusive events, and $p_A(\mathcal{A}_{IE})$ is the probability of one or more igneous eruptive events.

The scenario classes $\mathcal{A}_{II}$ and $\mathcal{A}_{IE}$ are not disjoint. However, if the question is asked “What is the probability of an igneous event?” or “What is the probability of an igneous intrusive event?”, then most likely $p_A(\mathcal{A}_{II}) = p_A(\mathcal{A}_I)$ is the desired answer. Similarly, if the question is asked “What is the probability of an igneous eruptive event?”, then most likely $p_A(\mathcal{A}_{IE})$ is the desired answer. If desired, disjoint scenario classes involving igneous intrusive and igneous eruptive scenario classes and their associated probabilities can be defined in the same manner as indicated in Eqs. (2.4)–(2.7) of Ref. [8] for early waste package (WP) failure and early drip shield (DS) failure. Although possible, such definitions are not very useful computationally.

No synergisms are assumed to exist between the doses that result from the intrusive damage to WPs and the doses that result from the eruptive releases to the atmosphere; 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 igneous events and doses that result from other disruptions. As a result

$$D_I(\tau|\mathbf{a}, \mathbf{e}_M) = D_{II}(\tau|\mathbf{a}, \mathbf{e}_M) + D_{IE}(\tau|\mathbf{a}, \mathbf{e}_M), \tag{2.4}$$

where

$D_I(\tau|\mathbf{a}, \mathbf{e}_M)$ = dose to RMEI (mrem/yr) at time τ resulting from igneous events associated with element $\mathbf{a}$ of $\mathcal{A}$,

$D_{II}(\tau|\mathbf{a}, \mathbf{e}_M)$ = dose to RMEI (mrem/yr) at time τ resulting from intrusive damage to WPs for igneous events associated with element $\mathbf{a}$ of $\mathcal{A}$,

$D_{IE}(\tau|\mathbf{a}, \mathbf{e}_M)$ = dose to RMEI (mrem/yr) at time τ resulting from the eruptive releases to the atmosphere forigneous events associated with element $\mathbf{a}$ of $\mathcal{A}$,

and all results are conditional on the element $\mathbf{e} = [\mathbf{e}_A, \mathbf{e}_M]$ of the sample space $\mathcal{E}$ for epistemic uncertainty (see Sections 3–8 and App. B of Ref. [2]). If $\mathbf{a}$ involves no igneous intrusive damage to WPs, then $D_{II}(\tau|\mathbf{a}, \mathbf{e}_M) = 0$; similarly, if $\mathbf{a}$ involves no eruptive releases to the atmosphere, then $D_{IE}(\tau|\mathbf{a}, \mathbf{e}_M) = 0$.

Summary descriptions of the models that produce $D_I(\tau|\mathbf{a}, \mathbf{e}_M)$, $D_{II}(\tau|\mathbf{a}, \mathbf{e}_M)$ and $D_{IE}(\tau|\mathbf{a}, \mathbf{e}_M)$ are given in Section 5 of Ref. [13] and Section 6 of Ref. [1], and more detailed descriptions are available in the reports cited in Refs. [1,13] and in App. B of Ref. [2]. In addition, an extensive description of the development process that led to the models that produce $D_I(\tau|\mathbf{a}, \mathbf{e}_M)$, $D_{II}(\tau|\mathbf{a}, \mathbf{e}_M)$ and $D_{IE}(\tau|\mathbf{a}, \mathbf{e}_M)$ is given in Refs. [14–23].

With the following exceptions, the models summarized in Fig. 2 of Ref. [13] for the nominal scenario class are the same as those used to determine $D_{II}(\tau|\mathbf{a}, \mathbf{e}_M)$. In the igneous intrusive scenario class, the model for drift seepage is replaced by the assumption that, subsequent to an igneous intrusive event, seep-age into a repository drift is equal to the percolation flux over the drift cross-sectional area, and the model for drift wall condensation is not used ([13], Section 5). These changes reflect the conceptual model that fluid flow though a drift filled with cooled magma would resemble flow through fractured basalt. Also, at the time of an igneous intrusive event, the DSs and WPs are assumed to fail and thereafter provide no barrier to water flow or radionuclide transport. This assumption simplifies the representation of the effects of an igneous intrusive event on the engineered barrier components in a conservative manner. Subsequent to an igneous intrusive event, drift temperatures are perturbed for approximately 100 yr to represent the addition of heat with the intrusive body ([1], Section 6.5.1.1.2 and [24], Section 6.6.6). The elevated temperatures, when applied in the models for waste form degradation, greatly accelerate these processes, and generally result in rapid degradation of all waste forms ([1], Section 6.5.1.1 and [13], Sections 3.13 and 5). In addition, the models for the engineered barrier system (EBS) chemical environment and for radionuclide mobilization are modified to account for the silica available to percolating waters from the igneous material surrounding the WPs ([1], Section 6.3.7.5.2). A very different model structure is used to determine $D_{IE}(\tau|\mathbf{a}, \mathbf{e}_M)$ (Fig. 1; see [13], Section 5, for additional details).

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

$$\begin{aligned}\overline{D}_I(\tau|\mathbf{e}) &= \int_{\mathcal{A}_I} D_I(\tau|\mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A \\ &= \int_{\mathcal{A}_I} [D_{II}(\tau|\mathbf{a}, \mathbf{e}_M) + D_{IE}(\tau|\mathbf{a}, \mathbf{e}_M)] d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A \\ &= \int_{\mathcal{A}_I} D_{II}(\tau|\mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A + \int_{\mathcal{A}_I} D_{IE}(\tau|\mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A \\ &= \overline{D}_{II}(\tau|\mathbf{e}) + \overline{D}_{IE}(\tau|\mathbf{e}),\end{aligned} \tag{2.5}$$

where (i)

$$\begin{aligned}\overline{D}_{II}(\tau|\mathbf{e}) &= \int_{\mathcal{A}_I} D_{II}(\tau|\mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A \\ &= \int_{\mathcal{A}_{II}} D_{II}(\tau|\mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A\end{aligned} \tag{2.6}$$

is the expected dose to the RMEI (mrem/yr) at time τ resulting from igneous intrusive events, (ii)

$$\begin{aligned}\overline{D}_{IE}(\tau|\mathbf{e}) &= \int_{\mathcal{A}_I} D_{IE}(\tau|\mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A \\ &= \int_{\mathcal{A}_{IE}} D_{IE}(\tau|\mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a}|\mathbf{e}_A)\mathrm{d}A\end{aligned} \tag{2.7}$$

is the expected dose to the RMEI (mrem/yr) at time τ resulting from igneous eruptive events, (iii) $d_{\mathcal{A}}(\mathbf{a}|\mathbf{e}_{\mathcal{A}})$ is the density function associated with the probability space $(\mathcal{A}, \mathbb{A}, p_{\mathcal{A}})$ for aleatory uncertainty ([2], Section 3), and (iv) all results are conditional on the element $\mathbf{e} = [\mathbf{e}_A, \mathbf{e}_M]$ of $\mathcal{E}$. The conversion from an integral over $\mathcal{A}_I$ to an integral over $\mathcal{A}_{II}$ in Eq. (2.6) is only notational as $\mathcal{A}_I = \mathcal{A}_{II}$; the conversion from an integral over $\mathcal{A}_I$ to an integral over $\mathcal{A}_{IE}$ in Eq. (2.7) is possible because $D_{IE}(\tau|\mathbf{a}, \mathbf{e}_M) = 0$ if $\mathbf{a} \notin \mathcal{A}_{IE}$.

The general form of the elements $\mathbf{a}$ of $\mathcal{A}$ is shown in Eqs. (6.1)–(6.8) of Ref. [2]. However, because no synergisms between disruptions are assumed in the determination of $\overline{D}_{II}(\tau|\mathbf{e})$ and $\overline{D}_{IE}(\tau|\mathbf{e})$, the representations for the elements of $\mathcal{A}_{II}$ and $\mathcal{A}_{IE}$ can be simplified to

$$\mathbf{a}_{II} = [nII, \mathbf{a}_{II,1}, \mathbf{a}_{II,2}, \ldots, \mathbf{a}_{II,nII}] \tag{2.8}$$

and

$$\mathbf{a}_{IE} = [nIE, \mathbf{a}_{IE,1}, \mathbf{a}_{IE,2}, \ldots, \mathbf{a}_{IE,nIE}], \tag{2.9}$$

respectively. With this notation, the elements $\mathbf{a}_{II}$ of $\mathcal{A}_{II}$ only contain representations for igneous intrusive events (i.e., the $\mathbf{a}_{II,j}$; see Eq. (3.1)), and the elements $\mathbf{a}_{IE}$ of $\mathcal{A}_{IE}$ only contain representations for igneous eruptive events (i.e., the $\mathbf{a}_{IE,j}$; see Eq. (4.1)).