Reliability Engineering and System Safety 122 (2014) 380–398

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

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

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ARTICLE INFO

Available online 20 July 2013

Keywords:
Aleatory uncertainty
Epistemic uncertainty
Expected dose
Seismic fault displacement scenario class
Seismic ground motion scenario class
Radioactive waste disposal
Uncertainty analysis
Yucca Mountain

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 seismic ground motion scenario class and the seismic fault displacement scenario class in the 2008 YM PA. The following topics are addressed: (i) definition of the seismic scenario classes and the determination of dose and expected dose to the RMEI, (ii) properties of the seismic ground motion scenario class, (iii) expected dose and uncertainty in expected dose to the RMEI for the seismic ground motion scenario class from 0 to 20,000 yr, (iv) expected dose and uncertainty in expected dose to the RMEI for the seismic ground motion scenario class from 0 to 10^6 yr, (v) properties of the seismic fault displacement scenario class including expected dose and uncertainty in expected dose to the RMEI from 0 to 20,000 yr and 0 to 10^6 yr, (vi) expected dose and uncertainty in expected dose to the RMEI for the combined ground motion and seismic fault displacement scenario class, and (vii) probabilities associated with seismic 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 the 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 seismic events. Specifically, two types of seismic events are considered in the 2008 YM PA: seismic ground motion events and seismic fault displacement events. This presentation describes the determination of expected dose from seismic 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 ([3]; [4]; [2], Section 2) and presents associated uncertainty analysis results.

The following topics are considered: properties of the seismic scenario classes and the determination of dose and expected dose the RMEI (Section 2), the seismic ground motion scenario class (Section 3), expected dose and uncertainty in expected dose to the RMEI for the seismic ground motion scenario class from 0 to 20,000 yr (Section 4), expected dose and uncertainty in expected dose to the RMEI for the seismic ground motion scenario class from 0 to 10^6 yr (Section 5), the seismic fault displacement scenario class including expected dose and uncertainty in expected dose to the RMEI from 0 to 20,000 yr and 0 to 10^6 yr (Section 6), expected dose and uncertainty in expected dose to the RMEI for the seismic scenario class (Section 7), and probabilities associated with seismic scenario classes (Section 8). The presentation then ends with a concluding summary discussion (Section 9).

A following presentation presents extensive uncertainty and sensitivity analyses related to the determination of dose and

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http://dx.doi.org/10.1016/j.ress.2013.06.015

expected dose to the RMEI for the seismic scenario classes [5]. Additional presentations consider the nominal scenario class [6,7], early failure scenario classes [8,9], igneous scenario classes [10,11], and all scenario classes together [12].

2. Seismic scenario classes: $\mathcal{A}_S$, $\mathcal{A}_{SG}$ and $\mathcal{A}_{SF}$

The seismic ground motion scenario class and the seismic fault displacement scenario class are defined by the sets

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

and

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

as indicated in Eqs. (6.17) and (6.18) of Ref. [2]. In the preceding, $\mathcal{A}$ is the sample space for aleatory uncertainty defined in Section 6 of Ref. [2], and nSG and nSF are the number of seismic ground motion events and seismic fault displacement events, respectively, associated with the element $\mathbf{a}$ of $\mathcal{A}$. Further, the seismic scenario class $\mathcal{A}_S$ is defined by

$$\mathcal{A}_S = \mathcal{A}_{SG} \cup \mathcal{A}_{SF} = \{\mathbf{a} : \mathbf{a} \in \mathcal{A} \text{ and } nSG \geq 1 \text{ or } nSF \geq 1\} \tag{2.3}$$

as indicated in Eq. (6.12) of Ref. [2]. In turn, $p_A(\mathcal{A}_{SG})$ is the probability of one or more seismic ground motion events; $p_A(\mathcal{A}_{SF})$ is the probability of one or more seismic fault displacement events; and $p_A(\mathcal{A}_S)$ is the probability of one or more seismic events.

The scenario classes $\mathcal{A}_S$, $\mathcal{A}_{SG}$ and $\mathcal{A}_{SF}$ are not disjoint. However, if the question is asked "What is the probability of a seismic event?," then most likely $p_A(\mathcal{A}_S)$ is the desired answer. If the question is asked "What is the probability of a seismic ground motion event?", then most likely $p_A(\mathcal{A}_{SG})$ is the desired answer. Similarly, if the question is asked "What is the probability of a seismic fault displacement event?", then most likely $p_A(\mathcal{A}_{SF})$ is the desired answer. If desired, disjoint scenario classes involving seismic events 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.

No synergisms are assumed to exist between the doses that result from the seismic ground motion damage to WPs and the doses that result from seismic fault displacement damage to WPs. Further, as indicated in conjunction with Eq. (7.1) of Ref. [2], no synergisms are assumed to exist between doses that result from seismic events and doses that result from other disruptions. As a result,

$$D_S(\tau|\mathbf{a}, \mathbf{e}_M) = D_{SG}(\tau|\mathbf{a}, \mathbf{e}_M) + D_{SF}(\tau|\mathbf{a}, \mathbf{e}_M), \tag{2.4}$$

where

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

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

$D_{SF}(\tau|\mathbf{a}, \mathbf{e}_M)$ = dose to RMEI (mrem/yr) at time τ resulting from fault displacement damage to WPs for seismic 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. If $\mathbf{a}$ involves no seismic ground motion damage to WPs, then $D_{SG}(\tau|\mathbf{a}, \mathbf{e}_M) = 0$; similarly, if $\mathbf{a}$ involves no seismic fault displacement damage to WPs, then $D_{SF}(\tau|\mathbf{a}, \mathbf{e}_M) = 0$.

The 2008 YM PA incorporates the effects of a vector $\mathbf{e} = [\mathbf{e}_A, \mathbf{e}_M]$ of epistemically uncertain analysis inputs, where the elements of $\mathbf{e}_A$ are epistemically uncertain quantities involved in the characterization of aleatory uncertainty and the elements of $\mathbf{e}_M$ are epistemically uncertain quantities involved in the modeling of physical processes ([2], Section 3). The indicated sample space $\mathcal{E}$ for epistemic uncertainty contains the possible values for $\mathbf{e}$. A complete listing of the elements of $\mathbf{e}$ is given in App. B of Ref. [2].

The overall structure of the modeling processes that determine $D_{SG}(\tau|\mathbf{a}, \mathbf{e}_M)$ and $D_{SF}(\tau|\mathbf{a}, \mathbf{e}_M)$ is shown in Fig. 6.1.4–6 of Ref. [1] and is similar to the structure shown in Fig. 2 of Ref. [13] for the nominal scenario class. The primary differences in the models used for the seismic scenario classes and the nominal scenario class relate to the effects of seismic events on WPs and the engineered barrier system (EBS). Summary descriptions of the models that produce $D_S(\tau|\mathbf{a}, \mathbf{e}_M)$, $D_{SG}(\tau|\mathbf{a}, \mathbf{e}_M)$ and $D_{SF}(\tau|\mathbf{a}, \mathbf{e}_M)$ 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 App. B of Ref. [2]. Further, an extensive description of the development process that led to the models that produce $D_S(\tau|\mathbf{a}, \mathbf{e}_M)$, $D_{SG}(\tau|\mathbf{a}, \mathbf{e}_M)$ and $D_{SF}(\tau|\mathbf{a}, \mathbf{e}_M)$ is given in Refs. [14–23].

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

$$\begin{aligned}\overline{D}_S(\tau|\mathbf{e}) &= \int_{\mathcal{A}_S} D_S(\tau|\mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a}|\mathbf{e}_A)\, dA \\ &= \int_{\mathcal{A}_S} [D_{SG}(\tau|\mathbf{a}, \mathbf{e}_M) + D_{SF}(\tau|\mathbf{a}, \mathbf{e}_M)] d_A(\mathbf{a}|\mathbf{e}_A)\, dA \\ &= \int_{\mathcal{A}_S} D_{SG}(\tau|\mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a}|\mathbf{e}_A)\, dA + \int_{\mathcal{A}_S} D_{SF}(\tau|\mathbf{a}, \mathbf{e}_M) d_A(\mathbf{a}|\mathbf{e}_A)\, dA \\ &= \overline{D}_{SG}(\tau|\mathbf{e}) + \overline{D}_{SF}(\tau|\mathbf{e}),\end{aligned} \tag{2.5}$$

where (i)

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

is the expected dose to the RMEI (mrem/yr) at time τ resulting from seismic ground motion events, (ii)

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

is the expected dose to the RMEI (mrem/yr) at time τ resulting from seismic fault displacement events, (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 $\mathbf{e} = [\mathbf{e}_A, \mathbf{e}_M]$ of $\mathcal{E}$. The conversion from an integral over $\mathcal{A}_S$ to an integral over $\mathcal{A}_{SG}$ in Eq. (2.6) is possible because $D_{SG}(\tau|\mathbf{a}, \mathbf{e}_M) = 0$ if $\mathbf{a} \notin \mathcal{A}_{SG}$; similarly, the conversion from an integral over $\mathcal{A}_S$ to an integral over $\mathcal{A}_{SF}$ in Eq. (2.7) is possible because $D_{SF}(\tau|\mathbf{a}, \mathbf{e}_M) = 0$ if $\mathbf{a} \notin \mathcal{A}_{SF}$.

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 $\overline{D}_{SG}(\tau|\mathbf{e})$ and $\overline{D}_{SF}(\tau|\mathbf{e})$, the representations for the elements of $\mathcal{A}_{SG}$ and $\mathcal{A}_{SF}$ can be simplified to

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

and

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

respectively. With this notation, the elements $\mathbf{a}_{SG}$ of $\mathcal{A}_{SG}$ only contain representations for seismic ground motion events (i.e., the $\mathbf{a}_{SG,j}$; see Eq. (3.1)), and the elements $\mathbf{a}_{SF}$ of $\mathcal{A}_{SF}$ only contain representations for seismic fault displacement events (i.e., the $\mathbf{a}_{SF,j}$; see Eq. (6.1)).