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Expected dose and associated uncertainty and sensitivity analysis results for the human intrusion scenario 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 (mean) dose to the reasonably maximally exposed individual (RMEI) specified in the NRC regulations for the YM repository resulting from an inadvertent drilling intrusion into the repository. The following topics are addressed: (i) assumed properties of an inadvertent drilling intrusion and the determination of the associated dose and expected (mean) dose to the RMEI, (ii) uncertainty and sensitivity analysis results for expected dose to the RMEI, and (iii) the numerical stability of the sampling-based procedure used to estimate expected (mean) 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 describes analyses performed as part of the 2008 YM performance assessment (PA) to assess compliance with the Individual Protection Standard for Human Intrusion. Specifically, the determination of expected (mean) dose to the RMEI resulting from an inadvertent drilling intrusion is described, and associated uncertainty and sensitivity analysis results are presented. The following topics are considered: regulatory background (Section 2); structure of analysis used to determine dose, expected dose, uncertainty in dose and expected dose, and resultant expected (mean) dose to the RMEI (Section 3); uncertainty in expected dose to the RMEI and associated sensitivity analysis results (Section 4); and numerical stability of the sampling-based procedure used to estimate expected (mean) dose to

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the RMEI (Section 5). The presentation then concludes with a summary discussion (Section 6).

Summaries of the analyses performed in the 2008 YM PA to assess compliance with the Individual Protection Standard after Permanent Closure and the Standards for Protection of Ground Water are presented in Refs. [3,4], respectively. Further, more detailed results underlying the assessment of compliance with the Individual Protection Standard after Permanent Closure are presented in Refs. [5–13], and a summary of the entire 2008 YM PA is available in Ref. [14].

2. Regulatory background

The human intrusion scenario is specified by the NRC in 10 CFR 63.322 as follows [1,2]:

§ 63.322 Human intrusion scenario. For the purposes of the analysis of human intrusion, DOE must make the following assumptions:

(a) There is a single human intrusion as a result of exploratory drilling for groundwater.
(b) The intruders drill a borehole directly through a degraded waste package into the uppermost aquifer underlying the Yucca Mountain repository.
(c) The drillers use the common techniques and practices that are currently employed in exploratory drilling for groundwater in the region surrounding Yucca Mountain.
(d) Careful sealing of the borehole does not occur; instead natural degradation processes gradually modify the borehole.
(e) No particulate waste material falls into the borehole.
(f) The exposure scenario includes only those radionuclides transported to the saturated zone by water (e.g., water enters the waste package, releases radionuclides, and transports radionuclides by way of the borehole to the saturated zone).
(g) No releases are included that are caused by unlikely natural processes and events.

The results for this scenario are compared with the individual protection standard for a human intrusion of the repository defined in 10 CFR 63.321 [1,2]:

§ 63.321 Individual protection standard for human intrusion. DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion could occur without recognition by the drillers. DOE must:

(a) Provide the analyses and its technical bases used to determine the time of occurrence of human intrusion (§ 63.322) without recognition by the drillers.
(b) If complete waste package penetration is projected to occur at or before 10,000 years after disposal:
    (1) Demonstrate that there is a reasonable expectation that the reasonably maximally exposed individual receives no more than an annual dose of 0.15 mSv (15 mrem) as a result of a human intrusion, at or before 10,000 years after disposal. The analysis must include all potential environmental pathways of radionuclide transport and exposure subject to the requirements at § 63.322; and
    (2) If exposures to the reasonably maximally exposed individual occur more than 10,000 years after disposal, include the results of the analysis and its bases in the environmental impact statement for Yucca Mountain as an indicator of long-term disposal system performance.
(c) Include the results of the analysis and its bases in the environmental impact statement for Yucca Mountain as an indicator of long-term disposal system performance, if the intrusion is not projected to occur before 10,000 years after disposal.

The NRC specifies that the DOE must determine the earliest time after disposal that a waste package (WP) would degrade sufficiently that a human intrusion could occur without recognition by the drillers. In addition, by way of explanation and corroboration per 10 CFR 63.321(a) [1;2], the DOE must provide the analyses and technical basis used to determine the time of occurrence of human intrusion, as described in NRC proposed rule in 10 CFR 63.322 [1;2], without recognition by the drillers. Analysis presented in Section 6.7.2 of Ref. [14] identified 200,000 yrs after closure as the earliest time of intrusion.

3. Analysis structure

Conceptually, the analysis for the human intrusion scenario is structured in the same manner as the analyses for the other scenario classes in the 2008 YM PA [5–13]. As described in Ref. [5], the same three basic entities underlie the conceptual structure of the human intrusion scenario as underlie the early failure, igneous and seismic scenarios: (i) EN1, a probabilistic characterization of what could occur at the facility under consideration; (ii) EN2, mathematical models for estimating the consequences of what could occur; and (iii) EN3, a probabilistic characterization of the uncertainty in the parameters used in the definitions of EN1 and EN2. For the human intrusion scenario, EN1 corresponds to a probability space $(\mathcal{A}, \mathbb{A}, p_A)$ that characterizes the uncertainty in the location of a single drilling intrusion at 200,000 yr after repository closure; EN2 corresponds to the models used to estimate radionuclide transport after the intrusion occurs ([15], Fig. 2; also, [14], Fig. 6.1.4-7); and EN3 corresponds to a probability space $(\mathcal{E}, \mathbb{E}, p_E)$ that characterizes the uncertainty in the possible values of parameters that are used in EN1 and EN2. The elements $\mathbf{e}$ of the sample space $\mathcal{E}$ for epistemic uncertainty correspond to the variables listed in Appendix B of Ref. [5]; however, not all variables listed in Appendix B of Ref. [5] are used in the human intrusion scenario.

In the human intrusion scenario, each element $\mathbf{a}$ of the sample space $\mathcal{A}$ for aleatory uncertainty is a vector of the form

$$\mathbf{a} = [WPT, PB, SZL] \tag{3.1}$$

describing the properties of a single drilling intrusion that intersects a WP in the repository, where (i) WPT indicates the type of WP intersected by the drilling intrusion, with $WPT=1$ indicating intersection with a commercial spent nuclear fuel (CSNF) WP and $WPT=2$ indicating intersection with a codisposed spent nuclear fuel (CDSP) WP ([14], Section 6.3.7.1), (ii) $PB=1$, 2, 3, 4 or 5 indicates the percolation bin in which the intersected WP package is located, with $PB=k$ indicating that the intersected WP is in percolation bin k ([7], Fig. 2), and (iii) $SZL=1$, 2, 3 or 4 indicates the saturated zone (SZ) location intersected by the drilling intrusion, with $SZL=l$ indicating that location l is intersected ([14], Fig. 6.3.10-6).

In turn, the probabilities for WPT and PB are defined by (i) $p_A(WPT)=0.71$ and 0.29 for $WPT=1$ and 2, respectively ([14], Table 6.3.7-1) and (ii) $p_A(PB)=0.05$, 0.25, 0.40, 0.25 and 0.05 for $PB=1$, 2, 3, 4 and 5, respectively ([14], Table 6.3.2-2). The probabilities for SZL are conditional on the value for PB ([14], Table 6.7-7; also [14], Figs. 6.3.9-6 and 6.3.10-6). For example, $p_A(SZL|PB=5)=0.61$, 0.00, 0.39 and 0.00 for $SZL=1$, 2, 3 and 4, respectively. The sample space $\mathcal{A}$ has a total of 35 elements as a