Reliability Engineering and System Safety 122 (2014) 406–420

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

Uncertainty and sensitivity analysis for the seismic scenario classes in the 2008 performance assessment for the proposed high-level radioactive waste repository at Yucca Mountain, Nevada

C.W. Hansen [a,*], G.A. Behie [b], A. Bier [a], K.M. Brooks [c], Y. Chen [d], J.C. Helton [a], S.P. Hommel [e], K.P. Lee [f], B. Lester [e], P.D. Mattie [a], S. Mehta [g], S.P. Miller [a], C.J. Sallaberry [a], S.D. Sevougian [a], P. Vo [a]

[a] Sandia National Laboratories, Albuquerque, NM 87185, USA
[b] AREVA Resources Canada Inc., Saskatoon, Saskatchewan S7K 3X5, Canada
[c] Southern Nevada Water Authority, Las Vegas, NV 89153, USA
[d] Navarro-Intera, LLC, Las Vegas, NV 89031, USA
[e] Savannah River Remediation, LLC, Aiken, SC 29808, USA
[f] AREVA Federal Services, Richland, WA 99354, USA
[g] INTERA Inc., Austin, TX 78754, USA

ARTICLE INFO

Available online 24 June 2013

Keywords:
Expected dose
Seismic ground motion scenario class
Seismic fault displacement scenario class
Performance assessment
Radioactive waste disposal
Sensitivity analysis
Uncertainty analysis
Yucca Mountain

ABSTRACT

Extensive work has been carried out by the US 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 US Nuclear Regulatory Commission (NRC), the DOE completed an extensive performance assessment (PA) for the proposed YM repository in 2008. This presentation describes uncertainty and sensitivity analysis results for the seismic ground motion scenario class and the seismic fault displacement scenario class obtained in the 2008 YM PA. The following topics are addressed for the seismic ground motion scenario class: (i) engineered barrier system conditions; (ii) release results for the engineered barrier system, unsaturated zone, and saturated zone; (iii) dose to the reasonably maximally exposed individual (RMEI) specified in the NRC regulations for the YM repository; and (iv) expected dose to the RMEI. In addition, expected dose to the RMEI for the seismic fault displacement scenario class is also considered. The present article is the 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

Uncertainty and sensitivity analysis are fundamental components of the 2008 performance assessment (PA) conducted by the US Department of Energy (DOE) for the proposed high-level radioactive waste repository at Yucca Mountain (YM), Nevada [1,2]. The following presentation describes the uncertainty and sensitivity analysis results obtained for the seismic scenario classes [3] in the 2008 YM PA. Additional presentations describe the uncertainty and sensitivity analysis results obtained in the 2008 YM PA for the nominal scenario class [4,5], early failure scenario classes [6,7], igneous scenario classes [8,9], and all scenario classes collectively [10].

The uncertainty and sensitivity techniques in use are described in Section 2 of Ref. [5]. The presented uncertainty and sensitivity analysis results are obtained with the first of the three replicated Latin hypercube samples (LHSs) described in Sections 11 and 12 of Ref. [2]. This is the same LHS used in the generation of the expected dose results for the seismic scenario classes [3] and also in the generation of results for the other scenario classes under consideration [4–9]. Descriptions of the epistemically uncertain analysis inputs under consideration and references to additional sources of information on these variables are given in Appendix B of Ref. [2]. Further, additional information on the uncertainty and sensitivity techniques in use is available in several reviews [11–14].

The following topics are considered in this presentation for the seismic ground motion scenario class for the time interval [0, 20,000 yr]: engineered barrier system (EBS) conditions

* Correspondence to: Sandia National Laboratories, P.O. Box 5800 Albuquerque 87185-1033, NM, USA. Tel.: +1 505 284 1643.
E-mail address: cwhanse@sandia.gov (C.W. Hansen).

0951-8320/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ress.2013.06.002

(Section 2), release from the EBS (Section 3), release from the unsaturated zone (UZ) (Section 4), release from the saturated zone (SZ) (Section 5), and dose to the reasonably maximally exposed individual (RMEI) (Section 6). Corresponding results are not presented for the time interval [0, 10^6 yr]. As described in Ref. [3], a sampling-based (i.e., Monte Carlo) procedure is used to propagate aleatory uncertainty for this time interval. Due to the use of this method, results were not obtained conditional on common elements from the sample space for aleatory uncertainty; as a result, sensitivity results for the effects of epistemic uncertainty analogous to those presented in Sections 2–6 are not available for the time interval [0, 10^6 yr]. However, the uncertainty and sensitivity results for expected dose to the RMEI are available for both time intervals (Section 7). In addition, expected dose to the RMEI for the seismic fault displacement scenario class is also considered (Section 8). The presentation then ends with a summary discussion (Section 9).

The primary focus of this presentation is on the uncertainty and sensitivity analysis results obtained for the seismic scenario classes. Summary descriptions of the models that underlie these results are given in Ref. [15] and in Section 6 of Ref. [1], and more detailed descriptions are available in the reports cited in Refs. [1,15] and in Appendix B of Ref. [2]. Further, an extensive description of the development process that led to these models is given in Refs. [16–25].

2. Seismic ground motion scenario class: EBS conditions over the time interval [0, 20,000 yr]

No other disruptive events (e.g., igneous intrusive events) are assumed to occur in the futures modeled for the seismic ground motion scenario class ([3], Section 2). Thus, the conditions in the EBS prior to a damaging seismic ground motion event are the same as described in Section 4 of Ref. [5] for the nominal scenario class. For the time interval [0, 20,000 yr], the most likely outcome of a damaging seismic ground motion event is stress corrosion cracking of all codisposed spent nuclear fuel (CDSP) waste packages (WPs) in the repository ([3], Section 4). Corresponding damage to commercial spent nuclear fuel (CSNF) WPs for this time period is sufficiently unlikely that it can be omitted from consideration ([1], Section 7.3.2.6.1). As a result, the evaluation of dose to the RMEI resulting from seismic ground motion events for the time interval [0, 20,000 yr] is considerably simplified by the need to consider only damage to CDSP WPs.

Prior to a damaging seismic ground motion event, WPs are intact and no degradation of waste forms is assumed to have occurred. The CDSP WPs are modeled as containing both high-level waste (HLW) and defense spent nuclear fuel (DSNF) ([15], Section 3.11). Subsequent to a damaging event, the DSNF waste forms are assumed to rapidly and completely degrade ([15], Section 3.13). In contrast, degradation of HLW depends on WP temperature and relative humidity and may proceed slowly over a long period of time, or may proceed rapidly if temperatures are elevated when the damaging event occurs. After a damaging seismic ground motion event, waste form degradation and chemical conditions ([15], Section 3.14) inside damaged WPs are generally similar to that described in Section 2.2 of Ref. [7] for the early WP failure scenario class.

3. Seismic ground motion scenario class: release from EBS over the time interval [0, 20,000 yr]

Releases from the EBS are summarized by the masses of radionuclides that move from the EBS into the UZ. Because only stress corrosion cracking damage to CDSP WPs is considered for the time interval [0, 20,000 yr], only diffusive transport from the WP is possible. Analyses are presented for the releases from the EBS of three radionuclides: (i) dissolved ^{237}Np, (ii) dissolved ^{239}Pu, and (iii) dissolved ^{99}Tc. Releases of radionuclides attached to colloids are low because colloid suspensions are generally unstable due to the relatively high ionic strengths of liquids interior to the WPs and are not presented here (see analogous results for early failure of CDSP WPs in Section 2.2 of Ref. [7]). Releases from the EBS begin soon after the damaging event because relative humidity inside CDSP WPs rises rapidly ([5], Fig. 14) and ^{237}Np is available to be mobilized from degraded DSNF waste forms. Because the event considered in the analysis occurs at 200 years after repository closure, releases are broadly similar to those observed for early failure of a CDSP WP ([7], Sections 3.3 and 3.4).

3.1. Movement of dissolved ^{237}Np: ESNP237 and ESNP237C

Uncertainty and sensitivity analyses for the time-dependent release rates (*ESNP237*, g/year) and cumulative releases (*ESNP237C*, g) over the time interval [0, 20,000 yr] for the movement of dissolved ^{237}Np from the EBS to the UZ resulting from a seismically induced fractional damaged area of 10^{-6} (32.6 m^2) at 200 years to all CDSP WPs in the repository are summarized in Fig. 1. The values for *ESNP237C* at 20,000 years fall between 10^{-2} and 10^{1} g (Fig. 1b). Thus, from a risk perspective, the values for *ESNP237* and *ESNP237C* for this analysis case are inconsequential because of their small sizes i.e., the dose resulting from dissolved ^{237}Np is much less than the dose resulting from other radionuclides such as ^{99}Tc ([3], Fig. 8a).

As indicated by the partial rank correlation coefficients (PRCCs) in Fig. 1c and d, the uncertainty in *ESNP237* and *ESNP237C* at early times is affected by *THERMCON* (host rock thermal conductivity level) and *INFIL* (infiltration level). The positive effects associated with these two variables at early times result from their role in decreasing the time at which the EBS cools to the level at which radionuclide movement is possible. A very early effect is also indicated for *DIAMCOLL* (diameter of colloid particles, nm); however, this effect occurs during the early period when the results are very noisy and also include many zero values. As a result, the selection of *DIAMCOLL* is probably spurious. As time increases, *GOESITED* (density of sorption sites on goethite, sites/nm^2) is the only variable with large PRCCs. In particular, the negative PRCCs associated with *GOESITED* indicate that *ESNP237* and *ESNP237C* decrease as *GOESITED* increases. This effect results because increasing *GOESITED* increases the amount of ^{237}Np sorbed onto goethite and thus reduces the amount of dissolved ^{237}Np available for release from the EBS.

As done in the preceding paragraph, an uncertain variable (e.g., *THERMCON*) is defined in the text the first time that it is referred to. Thereafter, only the variable name without definition is referred to. A complete definition for each uncertain variable in the 2008 YM PA, including range, distribution and sources of additional information, is given in Appendix B of Ref. [2].

As shown in Fig. 1a, the release rates of dissolved ^{237}Np after about 1000 years generally evolve toward a steady state value as environmental conditions inside the WP evolve toward steady state. These environmental variables determine the solubility of ^{237}Np at each time ([15], Section 3.15). This evolution is apparent in the changing values of the PRCCs for *DELPPCO2* (scale factor used to incorporate uncertainty into the value for the partial pressure of CO_2) and *PH2MCOS* (pointer variable used to incorporate uncertainty into pH in Cell 1b of CDSP WPs under liquid influx conditions; see [15], Section 3.14). The steady state release rate is determined by the balance between waste form degradation and reversible sorption onto ferrous corrosion products ([15], Section 3.17) as indicated by the PRCC for *GOESITED*. The effect of climate