Reliability Engineering and System Safety 122 (2014) 310–338

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

Uncertainty and sensitivity analysis for the early failure 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, S7K 3X5, Saskatchewan, 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 3 July 2013

Keywords:
Early drip shield failure
Early failure scenario classes
Early waste package failure
Performance assessment
Radioactive waste disposal
Sensitivity analysis
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 uncertainty and sensitivity analysis results for the early waste package failure scenario class and the early drip shield failure scenario class obtained in the 2008 YM PA. The following topics are addressed: (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. 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

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

Analyses for the early failure scenario classes determine the contribution to expected dose to the reasonably maximally exposed individual (RMEI) that results from waste packages (WPs) or drip shields (DSs) with manufacturing defects or undetected damage that occurred during emplacement [3]. These scenario classes involve only WPs or DSs which experience early failure. With two exceptions, the models used to estimate these contributions are the same as those used to determine the expected dose to the RMEI that results from nominal processes (i.e., in the absence of early failures, seismic events and igneous events; see [11], Section 4 and Fig. 2). In the early WP failure scenario class, the models for corrosion of the WP outer barrier are replaced by the assumption that, for early-failed WPs, the entire WP outer barrier is failed at time 0 and does not impede flow of water or transport of radionuclides ([11], Section 4; [1], Section 6.4). In 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 flow

* Correspondence to: Department 6112, Sandia National Laboratories, Albuquerque, NM 87185-1033, USA. Tel.: +1 505 284 1643.
E-mail address: cwhanse@sandia.gov (C.W. Hansen).

0951-8320/$ - see front matter
http://dx.doi.org/10.1016/j.ress.2013.06.029

of water onto the underlying WP ([11], Section 4; [1], Section 6.4.1.3). Further, (i) the entire outer barrier of a WP underlying an early-failed DS is assumed to fail if seepage occurs at the location of that DS and (ii) no WP failure is assumed to occur for a WP under an early-failed DS if seepage does not occur at the location of that DS. Analyses for early failures involving both commercial spent nuclear fuel (CSNF) WPs and codisposed spent nuclear fuel (CDSP) WPs are presented.

The uncertainty and sensitivity techniques in use are described in Section 2 of Ref. [5] and involve the use of Latin hypercube sampling, partial rank correlation coefficients (PRCCs) and stepwise rank regression. 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 early failure 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 extensive references to additional sources of information on these variables are given in App. B of Ref. [2]. Further, additional information on the uncertainty and sensitivity techniques in use is available in several reviews [12–15].

The following topics are considered in this presentation: engineered barrier system (EBS) conditions (Section 2), radionuclide movement from the EBS (Section 3), radionuclide movement from the unsaturated zone (UZ) (Section 4), radionuclide movement from the saturated zone (SZ) (Section 5), dose to the RMEI (Section 6), and expected dose to the RMEI (Section 7). The presentation then ends with a summary discussion (Section 8).

The primary focus of this presentation is on uncertainty and sensitivity analysis results obtained for the early WP and early DS failure scenario classes. Summary descriptions of the models that underlie these results are given in Ref. [11] and in Section 6 of Ref. [1], and more detailed descriptions are available in the reports cited in Refs. [1,11] and in App. B of Ref. [2]. Further, an extensive description of the development process that led to these models is given in Refs. [16–23].

2. Engineered barrier system (EBS) conditions

This section first describes conditions in the invert domain of the EBS (i.e., outside the WP) (Section 2.1) and then the conditions in the WP domain of the EBS (Section 2.2). The analysis examines conditions that directly influence (i) concentrations of radionuclides (i.e., ionic strength, pH and partial pressure of CO_2) or (ii) advective and/or diffusive transport of radionuclide either as dissolved species or associated with colloids (i.e., seepage rates, temperature, and relative humidity). EBS conditions for an early-failed WP or DS are those of the WP location selected as representative of a percolation bin (i.e., a portion of the repository area where percolation rates are similar; see [11], Section 3.4 and [5], Fig. 2).

2.1. Invert conditions

The environmental conditions in the invert domain of the EBS after early WP failures are the same as discussed and illustrated in Section 4 of Ref. [5] for nominal conditions.

For early DS failures under dripping conditions, the seepage rates, EBS temperatures, relative humidities and partial pressures for CO_2 are the same as for nominal conditions. However, the ionic strength and pH ([11], Section 3.6) in the invert associated with a failed DS under dripping conditions are different from the values present with an intact DS under dripping conditions (i.e., compare results in Figs. 1 and 2 for CSNF WPs with the corresponding 0 to 20,000 yr results in Figs. 17b and 19b of Ref. [5] for nominal conditions) because of interactions between seepage waters and WP materials. The results for CDSP WPs associated with a failed DS under dripping conditions are essentially the same as those in Figs. 1 and 2 for CSNF WPs ([1], Figs. K5.2-1b,f and K5.2-2b,f).

The uncertainty results for time-dependent ionic strength (mol/kg) in the invert are similar for CSNF WPs (*ISCSINAD*) and CDSP WPs (*ISCDINAD*) experiencing an early DS failure under dripping conditions in percolation bin 3 (Fig. 1a and [1], Fig. K5.2-1a). The transient behavior before about 600 yr results from the thermal evolution of the WPs (e.g., [24], Fig. 2.3.5-33). While the WPs are above 100 °C, ionic strength is not computed because no liquid water is present in the waste ([11], Section 3.18). During this time period, the ionic strength variable is assigned an artificial value of 1.0 to indicate that ionic strength is not computed. After WPs cool to below 100 °C, the uncertainty in the ionic strength results is dominated by *ISCSS* (pointer variable used to determine ionic strength in CSNF WP Cell 1 under dripping conditions; see Section 2.2 for definitions of Cells 1, 1a, 1b and 2) for CSNF WPs (Fig. 1b) and by *IS2MCOS* (pointer variable used to determine ionic strength in CDSP WP Cell 2, i.e., Cell 1b, under dripping conditions) for CDSP WPs ([1], Fig. K5.2-2f), with ionic strength increasing a s each of these variables increases. These two pointer variables select percentiles of time-varying log-triangular distributions ([25], Section 8.1.2) that summarize uncertainty in ionic strength arising primarily from uncertainty in water flux and steel

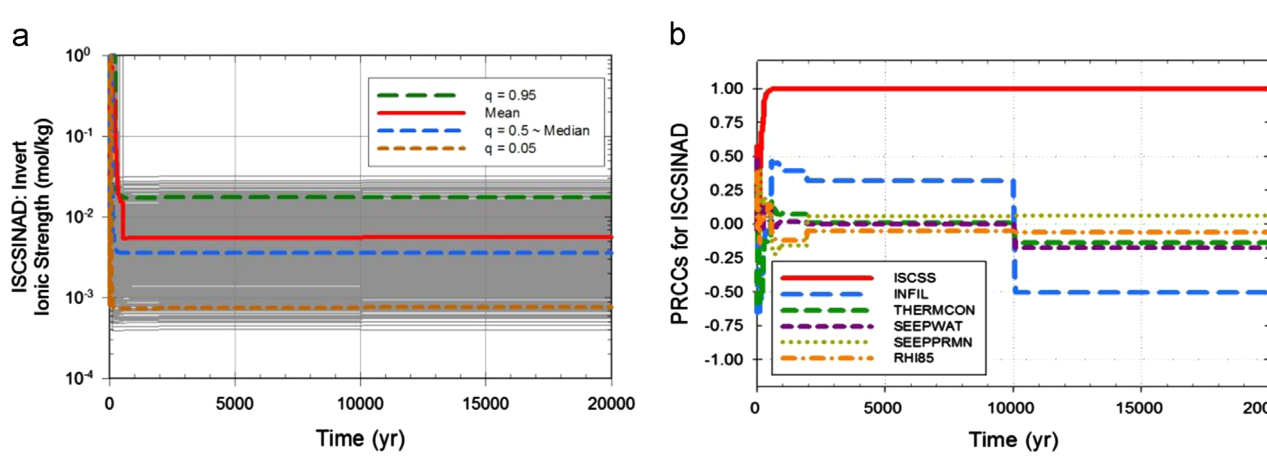

Fig. 1. Time-dependent ionic strength (mol/kg) in the invert for CSNF WPs (*ISCSINAD*) experiencing an early DS failure under dripping conditions in percolation bin 3: (a) *ISCSINAD* for all (i.e., 300) sample elements, and (b) PRCCs for ISCSINAD ([1], Fig. K5.2-1a,e); similar results hold for CDSP WPs ([1], Fig. K5.2-1b,f).