Reliability Engineering and System Safety 122 (2014) 207–222

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

Results from past performance assessments for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste

Rob P. Rechard *

Nuclear Waste Disposal Research & Analysis, Sandia National Laboratories, Albuquerque, NM 87185-0747, USA

ARTICLE INFO

Article history:
Received 3 June 2013
Accepted 14 June 2013
Available online 4 July 2013

Keywords:
Parameter sensitivity
Performance assessment
High-level radioactive waste
Radioactive waste disposal
Probabilistic risk assessment
Yucca Mountain

ABSTRACT

This paper summarizes the progression of results through four early performance assessments (PAs) conducted to support selection and to evaluate feasibility and three major PAs conducted to evaluate viability, recommend the site, and assess compliance of a repository for spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nevada. The early PAs in 1984, 1991, 1993, and 1995 evaluated cumulative release over 10^4 yr at a 10-km or 5-km boundary as specified in the draft and final 1985 radiation protection standard, respectively. During the early PAs, the fission products ^{99}Tc, ^{129}I, and activation products ^{14}C, and ^{36}Cl were identified as important radionuclides at the beginning of the regulatory period. The actinide, ^{237}Np, often dominated at the end of the regulatory period. Package and repository design options were evaluated during the early PAs but modeling did not identify strong preferences. In 1992 Congress mandated a change to a dose measure. Dose at a 20-km boundary from the repository was evaluated through 10^6 yr for the undisturbed scenario class via the groundwater pathway for the Congressionally mandated viability assessment in 1998. For the assessment for the site recommendation in 2000, doses from igneous eruption dominated in the first ~3000 yr, doses from igneous intrusion between ~3000 yr and ~40,000 yr, and doses from the undisturbed scenario class through 10^6 yr. The 2008 compliance assessment for the license application incorporated the influence of the seismic scenario class on waste package performance. The compliance assessment found that doses from the igneous intrusive scenario class and the combined undisturbed and seismic scenario class were important contributors at the ~18-km boundary. In the compliance PA, ^{99}Tc and ^{129}I fission products and ^{14}C activation product were important in the first 10^4 yr. Beyond 10^4 yr, actinides ^{239}Pu, ^{242}Pu, ^{237}Np, and ^{238}U decay product ^{226}Ra were important. In all PAs, parameters of the natural barrier were important, but in the three latter PAs, the slow degradation of the large, in-drift container had an important role in explaining the uncertainty in the peak dose.

1. Introduction

This paper summarizes the progression of results for performance assessments (PAs) since 1982 to provide historical context for the 2008 PA for the license application (PA-LA) to construct a repository at Yucca Mountain (YM). Located in southern Nevada, the repository was for the disposal of spent nuclear fuel from commercial reactors (CSNF), spent nuclear fuel owned by US Department of Energy (DSNF), and high-level radioactive waste (HLW) [1,2].[1] PA-LA, which is summarized in this special issue of *Reliability Engineering and System Safety*, underlies the Safety Analysis Report for the License Application (SAR/LA) submitted to the US Nuclear Regulatory Commission (NRC). Although the US Congress brought a *de facto* halt to the Yucca Mountain Project (YMP) by a lack of funding in 2010 and the Obama Administration began the process of formulating new policy, much understanding can be gleaned from the evolution of the modeling system and the effect of these changes on the results.

This paper also presents the progression of parameters whose uncertainty was important to explaining the spread in results. Companion papers present the two other major sources of uncertainty: scenario uncertainty in what features, events, and processes to include in models [4] and modeling uncertainty in how to include these features, events, and process [5–9]. These latter papers also provide more background on the parameters mentioned here. The history of the site selection, characterization, and repository design are also presented in companion papers [3,10,11].

* Tel.: +1 505 844 1761; fax: +1 505 844 2348.
E-mail address: rprecha@sandia.gov

[1] The text used to describe the PA and the underlying basis has grown tremendously, from two reports in 1982 and 1984, 219 and 78 pages long, respectively, to the 8578 page, 16 volume SAR, and supporting documentation in > 100 AMRs, many of which are over 500 pages long. Furthermore, the Licensing Support Network (LSN) for the NRC hearings contains over ~4.7 million e-mails and ~3.4 million documents [3, Appendix B].

0951-8320/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ress.2013.06.030

Table 1
Summary of PAs evaluating performance of repository at Yucca Mountain [2,13,15–19,21–29].

PA	Purpose	Design and models	Measure and key results
PA-EA [13,15]	Deterministic PA calculation for site selection in EA [35]	For eruptive dose used Gaussian plume model. For groundwater release, 33,000 stainless WP placed vertically and horizontally in drilled and blasted panels at 14 W/m^2 in 6 km^2 repository. WP fails at 300 yr, 1000 yr, or exponentially. 1-D model with source term and separate UZ and SZ fracture and matrix transport	Mean peak eruptive dose of 0.004 μSv/yr at 18 km from igneous eruption scenario (140 μSv/yr dose with probability of 2.9×10^{-5} over 10^4 yr). Cumulative release at 10 km from undisturbed scenario at 10^4 yr evaluated. For <1 mm/yr percolation (matrix flow), no release in 1st 10^4 yr. ^{129}I, with no sorption, was important (^{99}Tc adsorbed slightly). For >1 mm/yr percolation (fracture flow), ^{240}Pu and ^{239}Pu were important with ^{243}Am, ^{242}Pu, and ^{239}Np as minor contributors to release from 0.035 and 0.13
PACE-90	Deterministic PA calculation exercise		
PA-91 [16]	Demonstrate full stochastic PA capability and site feasibility with preliminary comparison to EPA and NRC criteria using simple models	Repository and WP design similar to PA-EA. WP fails between 500 and 10^4 yr. Two 1-D models of UZ water flow: ECM (most flow in matrix) and a weeps model (flow only in fractures). 1-D transport based on 2-D flow process model. Analysis added gas flow process model that also required WP heat process model	Cumulative release to 10^4 yr at 5 km from 3 scenarios: undisturbed, igneous eruption, and human intrusion. ^{99}Tc and ^{129}I important for groundwater flow in both ECM and weeps conceptual models. Gaseous releases from ^{14}C > groundwater > human intrusion > volcanic releases. SZ transport time ~1200 yr as in PA-EA. Percolation most important for ECM; aperture most important for weeps
PA-PNNL-91	Demonstrate PA with complex codes		
PA-93 [17]	Provide guidance on characterizing site and selecting options for heat and package placement in repository and demonstrate both dose and cumulative release measures	33,333 small WPs of Alloy 825 placed vertically in floor or 8500 large WPs with steel and Alloy 825 layers placed horizontally in bored drifts at 14 and 28 W/m^2 heat loads. Percolation change with climate added for 10^6 yr. Added thermal process module for percolation and improved container and waste degradation PA model to evaluate hot repository. 1-D transport based on 3-D flow particle paths. Analysis used ingestion table for calculating dose	Mean dose to 10^6 yr at 5 km from undisturbed scenario and cumulative release to 10^4 yr at 5 km from 3 scenarios (undisturbed, igneous intrusion, human intrusion) evaluated. ^{14}C gas largest portion of cumulative release; ^{99}Tc and ^{129}I important for high probability groundwater releases but ^{237}Np most important for low probability releases and peak dose; ^{237}Np release sensitive to percolation; WP steel layer offers little protection; vertical/horizontal placement and heat loading have only small influence
PA-M&O-93	Demonstrate PA with Rapid Integration Program (RIP) stochastic simulator		
PA-95 [18]	Improve modeling of EBS for comparison to EPA and NRC criteria	9582 WPs with stainless steel MPC handling canister, an Alloy 825 middle layer, and steel outer layer that are placed horizontally in bored drifts at 6 and 20 W/m^2. Used RIP stochastic simulator based on coupled thermal-hydrology process model; major PA model of container degradation with variability added, and 3 alternative models for EBS transport. PA included UZ flow from surface. 1-D transport using RIP based on 2-D flow from PA-91	Cumulative release to 10^4 yr and dose to 10^6 yr at 5 km from undisturbed scenario. ^{14}C, ^{99}Tc,^{129}I dominate cumulative releases; peak dose of ~300 μSv/yr from ^{237}Np, which depends on its solubility; bulk of container failure by 10^5 yr for either hot or cool repository; furthermore, failure distribution similar (hot repository protects longer but rate higher when resaturated); hence, thermal design only influences time and does not influence value of peak dose
PA-SNL-95 [22,23]	Demonstrate direct disposal of ~250 types of DSNF and evaluate treatment options for calcine HLW		
PA-96 [24]	Analyze direct disposal of excess Pu from dismantling weapons		
PA-97 [25]	Evaluate design options		
PA-VA (1998) [19]	Demonstrate viability to Congress of repository at YM using most current information as interpreted by expert panels	10,213 WPs with steel and Alloy 22 layers (20 mm thick) at 21 W/m^2, 3 km^2 repository with 28 m drift spacing. Major step in model complexity: added infiltration, drift seepage, EBS chemical environment, and biosphere transport process models. Greatly improved UZ flow (3-D dual permeability), thermal-hydrologic (used several scales), and WP model. Added particle tracking for UZ transport and convolution method for SZ transport	400 μSv/yr dose to 10^6 yr at 20 km for nominal scenario ($\mathcal{A}_{U+EF}$). In RIP, 177 parameters sampled. Sensitivity studies conducted for igneous eruption, igneous intrusion, igneous disruption of SZ; seismic rockfall, fault disruption of SZ. ^{99}Tc and ^{129}I dominate 1st 10^4 yr but very small; ^{237}Np dominates beyond 10^5 yr. DSNF usually contributes similar dose as HLW (assuming no cladding and fast, metallic corrosion rate) but less than CSNF. Doses from all disruptive events very small relative to nominal dose
LADS (1999) [26]	LA design study to evaluate options	Parameter values in nominal scenario changed to model design options	Ti drip shield added. Alloy 22 switched to outer container layer; containers spaced 0.1 m; drift support changed to steel mesh; drift spacing increased to 81 m
PA-SR (2000) [27]	Analysis to support recommending site under 10 CFR 963 using fully qualified software, parameters, and analysis	11,770 WPs with Alloy 22 outer layer (20 mm thick for CSNF; 25 mm for DSNF/HLW); stainless replaces carbon steel in 4.6 km^2 repository at 21 W/m^2. Waste blended to 11.8 kW/pkg. Added thermal-hydrologic-	Biosphere defined in draft 10 CFR 63 used to calculate dose to 10^6 yr at 20 km for 3 scenarios: $\mathcal{A}_{U+SGclad}$ (undisturbed with seismic cladding failure), $\mathcal{A}_{VE}$, and $\mathcal{A}_{VI}$. Waste particle size reduced, which causes $\mathcal{A}_{VE}$, dose