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Unsaturated flow modeling in performance assessments for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste

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ABSTRACT

This paper summarizes the progression of modeling efforts of infiltration, percolation, and seepage conducted between 1984 and 2008 to evaluate feasibility, viability, and assess compliance of a repository in the unsaturated zone for spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nevada. Scientific understanding of infiltration in a desert environment, unsaturated percolation flux in fractures and matrix of the volcanic tuff, and seepage into an open drift in a thermally perturbed environment was initially lacking in 1984. As understanding of the Yucca Mountain disposal system increased through site characterization and *in situ* testing, modeling of infiltration, percolation, and seepage evolved from simple assumptions in a single model in 1984 to three modeling modules each based on several detailed process models in 2008. Uncertainty in percolation flux through Yucca Mountain was usually important in explaining the observed uncertainty in performance measures: cumulative release in assessments prior to 1995 and individual dose, thereafter.

1. Introduction

Understanding the movement of water through porous and fractured volcanic tuff in the unsaturated zone (UZ) was a challenging scientific endeavor of the Yucca Mountain Project (YMP). This paper presents the progression of changes in modeling of infiltration at the surface, percolation through the mountain, and seepage into the repository drifts since 1984 to provide a historical perspective on the performance assessment (PA) for the 2008 license application (PA–LA), which is summarized in this special issue of *Reliability Engineering and System Safety*. PA–LA underlies the Safety Analysis Report (SAR/LA) submitted to the US Nuclear Regulatory Commission (NRC) in 2008 by the US Department of Energy (DOE) for constructing a repository at Yucca Mountain (YM) for high-level radioactive waste (HLW), commercial spent nuclear fuel (CSNF), and spent nuclear fuel owned by DOE (DSNF) (Fig. 1) [1,2]. Companion papers provide a historical summary of site selection and regulatory development by the US Environmental Protection Agency (EPA) and NRC [3]; hazards and scenarios identified [4]; repository design and site characterization conducted by YMP [5,6]; evolution of other models of the YM disposal system [7–9]; and past results [10].

The general progression of PA analysis and results of sensitivity analysis have been described by noting the changes in linkages of modules $\mathcal{M}^{\beta}$ for phenomena at spatial location β of the exposure pathway/consequence model $\mathcal{R}(\sim)$ [7] (Fig. 2). However, discussion of some of the assumptions, simplifications, and implementation within the various modules, as presented here for infiltration ($\mathcal{M}^{Infil}$), UZ percolation ($\mathcal{M}^{UZflow}$), and seepage into the repository ($\mathcal{M}^{Seep}$), is necessary to understand the information flowing through the linkages. These details help the reader get a glimpse of the complexity and the challenge of combining numerous simplified models in a PA simulation. A summary of the resulting empirical equations underlying the models is also necessary in order to define the parameters that were identified in sensitivity analysis as important in explaining the variation in performance measures (cumulative release R prior to 1998 and individual dose $D(t)$, thereafter) [10].

Large scale risk analysis must usually be conducted in several iterations to refine and focus the analysis on those aspects most pertinent to the policy issue [11, Fig. 3.2], and this iterative approach has indeed occurred at YMP. Seven PAs provide historical markers for the evolution of $\mathcal{M}^{Infil}$, $\mathcal{M}^{UZflow}$, and $\mathcal{M}^{Seep}$. Four early PA iterations to evaluate feasibility of the YM disposal system are discussed: a deterministic evaluation of the disposal

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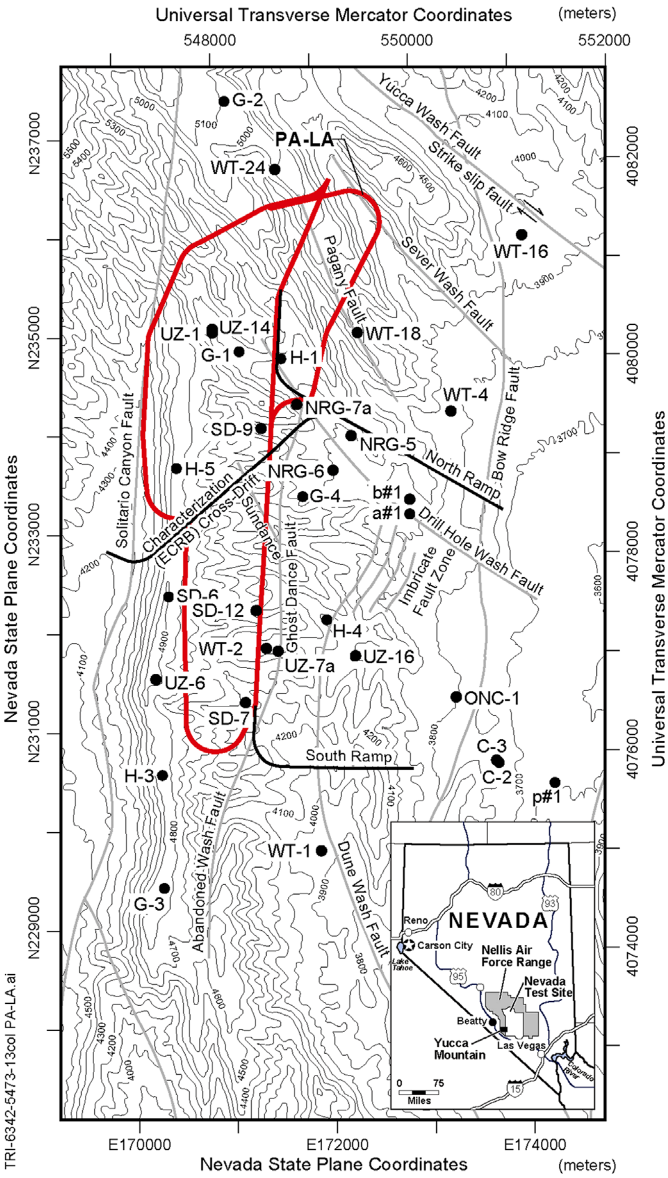

Fig. 1. Repository layout for PA–LA and pertinent wells at Yucca Mountain, Nevada.

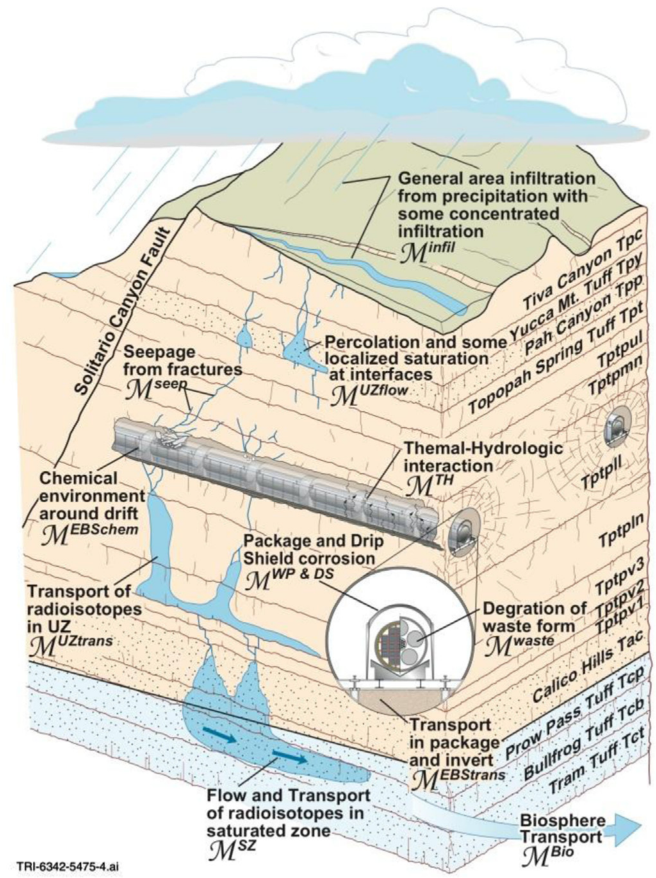

Fig. 2. Conceptualization of water and radionuclide movement and corresponding eleven modeling modules of PA-VA, PA-SR, and PA-LA at Yucca Mountain for the undisturbed scenario class.

system to support the draft and final environmental assessment of Yucca Mountain for further characterization, PA–EA [12,13]; the first stochastic simulation, PA-91 [14]; and two evaluations to provide guidance on repository design options, PA-93 [15] and PA-95 [16]. These four early PAs were followed by three PAs to support major decisions: a viability assessment, PA–VA, in 1998 [17]; an analysis for the site recommendation, PA–SR, in 2000 [18]; and the licensing application analysis, PA–LA, in 2008 [1,2].

2. UZ modeling for PA–EA

PA–EA was conducted to support the environmental assessment of the site for further characterization [6; 7, Appendix A; 10, Table 1]. In PA–EA, CSNF in 33,000 small, thin-walled stainless steel containers was placed either vertically in the floor or horizontally in pillars of rooms [5]. Catastrophic failure of the container was assumed to occur exponentially or at a fixed time between 300 and 1000 years [8]. Cumulative, normalized release ($R_U^{84}(\mathbf{e}^e)$) over 10^4 years to the accessible environment boundary 10 km from the repository (x^{ae}), the performance measure proposed in the draft EPA radiation protection standard 40 CFR 191 [3], was evaluated for the undisturbed scenario ($\mathcal{A}_U$) along a groundwater pathway as

$$R_{U,gw}^{84}(\mathbf{e}^e) = \sum_{r=1}^{n_U^r=17} \frac{1}{L_r f_{mass}} \int_0^{10^4\ \mathrm{yr}} \mathcal{R}_{U,gw,r}(t;\mathbf{e}^e)\Big|_{x^{ae}=10\ \mathrm{km}} dt \tag{1}$$

where f_{mass} is the mass fraction of metric tons of heavy metal (MTHM) in the repository (MTHM/10^3 MT); L_r is the limiting value specified in 40 CFR 191 for radionuclide r; $\mathbf{e}^e$ is an ordered nE-tuplet of epistemic model parameters, $\boldsymbol{e}=\{\varphi_1,..,\ \varphi_n,..,\varphi_{nE}\}$, which for PA–EA were deterministically varied; and $\mathcal{R}_{U,gw,r}(\sim)$ is the exposure pathway/consequence model for $\mathcal{A}_U$ that calculates the flux across a boundary. The consequence model $\mathcal{R}_{U,gw,r}(\sim)$ consisted of two model components for radionuclide transport in a single code [9]: (1) transport in fractures and matrix of the UZ ($\mathcal{M}^{UZ}$), and (2) transport in the matrix of the SZ ($\mathcal{M}^{SZ}$).

2.1. UZ percolation at repository horizon in PA–EA

Water percolation from the surface to the repository horizon was not simulated in PA–EA (although preliminary work had been conducted [19,20]). Rather, percolation at the repository level (q^{perc}) was set at 0.1 and 0.5 mm/yr for current conditions and at 5 and 20 mm/yr for a pluvial climate sometime in the future in *Ceterus parabis* sensitivity studies (i.e., q^{perc}~0.1, 0.5, 5, 20 mm/yr in precursor to $\mathcal{M}^{UZflow}$) [12, Table 8]. Although the model of regional water balance showed that no recharge was necessary at Yucca Mountain to explain flow patterns [21], the lower bound for