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Transport 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 modeling of radionuclide transport in the unsaturated and saturated zone conducted between 1984 and 2008 to evaluate feasibility, viability, and assess compliance of a repository for spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nevada. One dimensional (1-D) transport for a single porosity media without lateral dispersion was solved in both the saturated zone (SZ) and unsaturated zone (UZ) for the first assessment in 1984 but progressed to a dual-porosity formulation for the UZ in the second assessment in 1991. By the time of the viability assessment, a dual-permeability transport formulation was used in the UZ. With the planned switch to a dose performance measure, individual dose from a drinking water pathway was evaluated for the third assessment in 1993 and from numerous pathways for the viability assessment in 1998 and thereafter. Stream tubes for transport in the SZ were initially developed manually but progressed to particle tracking in 1991. For the viability assessment, particle tracking was used to solve the transport equations in the 3-D UZ and SZ flow fields. To facilitate calculations, the convolution method was also used in the SZ for the viability assessment. For the site recommendation in 2001 and licensing compliance analysis in 2008, the 3-D transport results of the SZ were combined with 1-D transport results, which evaluated decay of radionuclides, in order to evaluate compliance with groundwater protection requirements. Uncertainty in flow within the unsaturated and saturated zone was generally important to explaining the spread in the individual dose performance measure.

1. Introduction

This paper presents the evolution of transport modeling of radioactive waste to provide a helpful perspective on the performance assessment (PA) for the license application (PA-LA) for a repository at Yucca Mountain (YM) (Fig. 1). PA-LA underlies the Safety Analysis Report (SAR/LA) submitted by the United States (US) Department of Energy (DOE) [1,2], which is summarized in this special issue of *Reliability Engineering and System Safety*. Companion papers provide a historical summary of (a) site selection and regulatory development by the US Environmental Protection Agency (EPA) and US Nuclear Regulatory Commission (NRC) [3]; (b) hazards and scenarios identified [4]; and (c) site characterization and repository design [5,6].

The general progression of analysis of the YM repository has been summarized by noting the changes in linkages of the modules within the exposure pathway/consequence model [7]. However, presenting some of the simplifications within the unsaturated zone (UZ) transport module ($\mathcal{M}^{UZtrans}$) and the saturated zone (SZ) module ($\mathcal{M}^{SZ}$), as discussed here, is necessary to understand the information flowing through the linkages, along with the modeling evolution of other pertinent phenomena [8–10]. These details help the reader get a glimpse of the complexity and the challenge of using numerous model simplifications in a PA simulation for the Yucca Mountain Project (YMP). In addition, results of sensitivity analysis have been summarized elsewhere [11]; but, a brief summary of the equations underlying the models, as included here, is necessary to define the parameters that were identified as important in explaining the variance in performance measures (expected cumulative release $\overline{R}$ prior to 1998 and expected individual dose $\overline{D}(t)$], thereafter [3].

As understanding of the disposal system increased, $\mathcal{M}^{UZtrans}$ for the UZ (Fig. 2) and $\mathcal{M}^{SZ}$ have evolved from solution of one-dimensional

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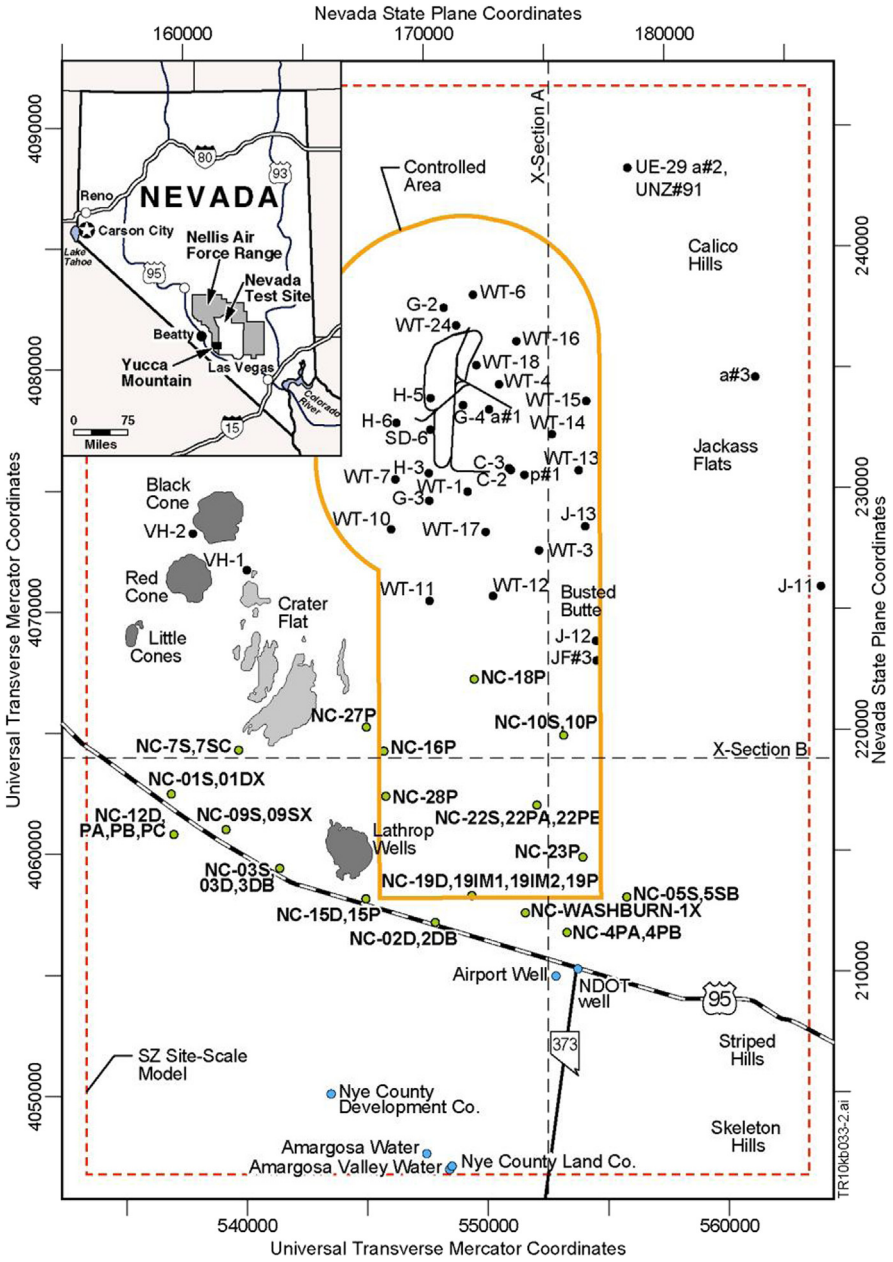

Fig. 1. Location of repository, controlled area, and pertinent wells at Yucca Mountain, Nevada.

(1-D) transport along manually developed stream tubes in 1984 to particle tracking in 3-D flow fields to solve the transport equations in 2008. Seven iterations of the PAs conducted to evaluate the YM disposal system provide historical markers for the evolution of $\mathcal{M}^{UZtrans}$ and $\mathcal{M}^{SZ}$. In PA–EA, the PA for the initial environmental assessment, the performance was evaluated deterministically [12,13]. PA-91, the first stochastic PA to evaluate site feasibility, serves as the second marker [14]. PA-91 was followed by two assessments in 1993, one conducted by the recently awarded management and operating (M&O) contractor, TRW (PA-M&O-93) [15]; and one conducted by Sandia National Laboratories (SNL) (PA-93) [16]. Only the latter is discussed herein [16, Fig. 1-1]. The next analysis discussed, PA-95, was conducted by the M&O contractor [17]. PA-93 and PA-95 provided preliminary guidance on the repository design options. These four early PAs were followed by three PAs to support major decisions. In 1997, the US Congress asked for a viability assessment, which was completed the following year (PA–VA) and serves as the fifth marker [18]. An analysis completed in 2000 for recommending the site—PA-SR—serves as the sixth marker [19]. The licensing case (PA-LA) serves as the final marker.

2. Transport modeling for PA–EA

PA–EA was conducted to support the environmental assessment (EA) to screen sites for further characterization [3]. In the analysis, commercial spent nuclear fuel (CSNF) contained in 33,000 small, thin-walled stainless steel packages was emplaced either vertically in the floor or horizontally in pillars of rooms blasted out of the volcanic tuff. Cumulative, normalized release ($R_U^{84}(\mathbf{e}^e)$) over 10^4 yr to the accessible environment boundary