Reliability Engineering and System Safety 122 (2014) 145–164

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

Waste package degradation from thermal and chemical processes in performance assessments for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste

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ARTICLE INFO

Available online 4 July 2013

Keywords:
Container degradation
High-level radioactive waste
Spent nuclear fuel
Radioactive waste disposal
Performance assessment
Yucca Mountain

ABSTRACT

This paper summarizes modeling of waste container degradation in performance assessments 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. As understanding of the Yucca Mountain disposal system increased, modeling of container degradation evolved from a component of the source term in 1984 to a separate module describing both container and drip shield degradation in 2008. A thermal module for evaluating the influence of higher heat loads from more closely packed, large waste packages was also introduced. In addition, a module for evaluating drift chemistry was added in later PAs to evaluate the potential for localized corrosion of the outer barrier of the waste container composed of Alloy 22, a highly corrosion-resistant nickel–chromium–tungsten–molybdenum alloy. The uncertainty of parameters related to container degradation contributed significantly to the estimated uncertainty of performance measures (cumulative release in assessments prior to 1995 and individual dose, thereafter).

1. Introduction

This paper presents the progression of changes since 1984 in the module for waste container degradation (which eventually included the drip shield) ($\mathcal{M}^{WP\&DS}$). This paper also presents the related modules for thermal hydrologic interactions ($\mathcal{M}^{TH}$) and chemical environment in the engineered barrier system (EBS) around the drift ($\mathcal{M}^{EBSchem}$).[1] The waste containers were intended to hold high-level radioactive waste (HLW), commercial spent nuclear fuel (CSNF), and spent nuclear fuel owned by the Department of Energy (DSNF). The purpose of the paper is to provide a historical perspective on the performance assessment (PA) for the license application (PA-LA) for a repository at Yucca Mountain (YM), 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 Nuclear Regulatory Commission (NRC) by Department of Energy (DOE) in 2008 [3,4].

The general progression of PA analyses and the results of sensitivity analysis have been described by noting the changes in linkages of 11 modules $\mathcal{M}^{\beta}$ for phenomena at spatial locations β of the exposure pathway/consequence model $\mathcal{R}(\sim)$ [5] (Fig. 1). However, discussing some of the assumptions, simplifications, and implementation within the various modules, as presented here for $\mathcal{M}^{WP\&DS}$, $\mathcal{M}^{TH}$, and $\mathcal{M}^{EBSchem}$, 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 within a PA simulation. A summary of the resulting empirical equations underlying the models is also necessary to define the parameters that were identified in sensitivity analysis as important in explaining the variation in performance measures (cumulative release R prior to 1995 and individual dose $D(t)$, thereafter) [6]. Companion papers provide a historical summary of site selection and regulatory development by NRC and the Environmental Protection Agency (EPA) [7]; hazards and scenarios identified [8]; and repository design and site characterization conducted by the Yucca Mountain Project (YMP) [9,10].

Seven PAs provide historical markers for the evolution of $\mathcal{M}^{WP\&DS}$, $\mathcal{M}^{TH}$, and $\mathcal{M}^{EBSchem}$ from merely components in the source term to separate modules composed of several linked models. Four

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[1] As defined by the NRC [1], the "*waste package* means the waste form and any containers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container." We discuss the waste form in a separate paper [2]; thus, this paper is primarily about the waste container; however, in the text we occasionally follow the informal practice of using the term waste package as synonymous with waste container, particularly, when using the acronym WP for waste package.

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http://dx.doi.org/10.1016/j.ress.2013.06.027

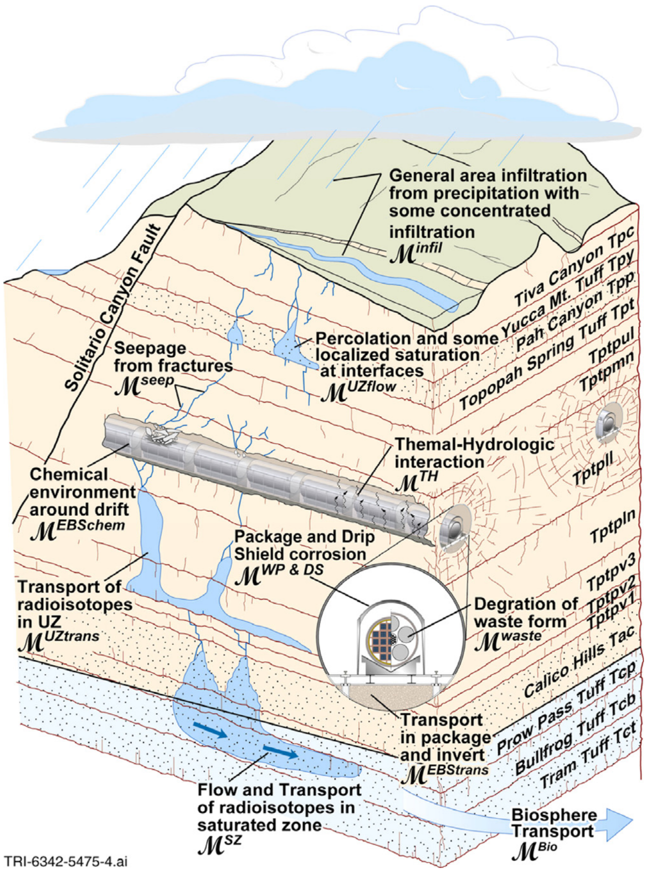

Fig. 1. Conceptualization of water and radionuclide movement and corresponding eleven modeling modules used in PA-VA, PA-SR, and PA-LA for Yucca Mountain for undisturbed scenario class.

early PA iterations to evaluate feasibility of the YM disposal system are discussed: a deterministic evaluation, PA-EA [11,12]; the first stochastic simulation, PA-91 [13]; and two evaluations to provide guidance on repository design options, PA-93 [14] and PA-95 [15]. These four early PAs were followed by three PAs to support major decisions: a viability assessment, PA-VA, in 1998 [16]; an analysis for the site recommendation, PA-SR, in 2001 [17]; and the licensing application analysis, PA-LA, in 2008 [3,4].

2. Container degradation in source-term of PA-EA

In 1982, Lawrence Livermore National Laboratory (LLNL) developed preliminary designs for HLW and CSNF waste packages based on drafts of proposed technical criteria in 10 CFR 60 [18]. By 1983, candidate materials for containers in the salt, basalt, and tuff repositories included stainless steel and high-nickel alloys [19,20]. Copper alloys such as proposed for the anoxic, saturated zone (SZ) in the Swedish repository concept were also evaluated as potential waste container materials but were less effective in the oxidizing, unsaturated zone (UZ) geologic setting at Yucca Mountain [21].[2]

PA-EA was conducted in 1984 to support the environmental assessment of the site for further characterization [10]. Cumulative, normalized release (R_U^{84}) over 10^4 yr to the accessible environment boundary (x^{ae}) 10 km from the repository, (the performance measure proposed in the draft EPA radiation

[2] In 1978, the Swedish package initially used a 6 mm thick titanium overpack around a stainless steel handling canister [22, p. 5.10]. By 1983, the Swedes settled on a thick copper alloy overpack for the canister.

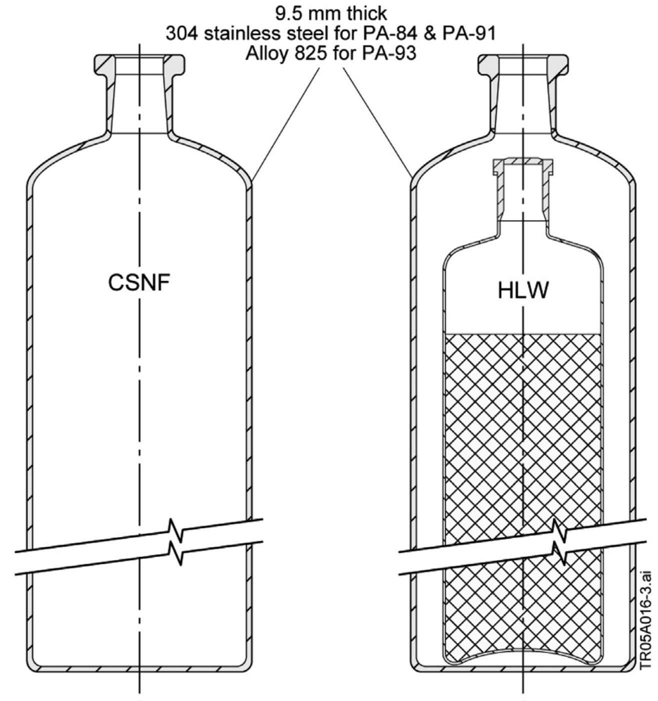

Fig. 2. Small, thin-walled container designs considered at time of PA-EA, PA-91 (SCP design), and PA-93, which maintained flexibility for disposal in various geologic media [14, Fig. 4-1; 24; 25, Figs. 3-9, 3-10; 26].

protection standards 40 CFR 191) was evaluated for the undisturbed scenario class ($\mathcal{A}_U$) [7]. Although other materials and designs were under consideration, only 10-mm thick containers of 304 stainless steel holding either HLW or CSNF were modeled in PA-EA (i.e., no engineered barrier such as a corrosion resistant overpack, adsorptive backfill, or borehole liner was modeled that would delay release of radionuclides). In PA-EA, CSNF packages were placed either vertically in the floor or horizontally in pillars [9, Table 2] (Fig. 2). About 33,000 packages were anticipated if the CSNF was not consolidated or ~18,000 packages if CSNF was consolidated at the repository by removing hardware surrounding the fuel rods [23,24].

The fraction of container degradation was modeled either as (1) instantaneous degradation, or (2) exponential degradation. For the instantaneous degradation, the cumulative fraction of containers failed was

$$F^{WP}(t) = \mathcal{H}(t - \tau^{fail}) \tag{1}$$

where the indicator function $\mathcal{H}\{x\} = 0$ if the argument $x \leq 0$; $\mathcal{H}\{x\} = 1$ if $x > 0$ and time of instantaneous degradation τ^{fail} was set at either 300 yr or 1000 yr, which corresponded to the range of minimum lifetime required in 10 CFR 60, Section 60.113. Instantaneous degradation accounted for the susceptibility of stainless steel to stress corrosion cracking (SCC).

For the alternative conceptual model of exponential degradation, the expected fraction of container failure was

$$F^{WP}(t) = 1 - exp\{-\lambda_{WP} t\} \tag{2}$$

and the mean time to failure ($1/\lambda_{WP}$) was set at 10^4 yr. The λ_{WP} could reasonably be assumed to include any protection of the waste such as degradation of the container and CSNF cladding (i.e, $\lambda_{WP} = \lambda_{can} + \lambda_{clad}$). Exponential degradation accounted for a portion of containers that failed early and the limited ability of water to initially enter containers through stress corrosion cracks.