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Hazards and scenarios examined for the Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste

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ABSTRACT

This paper summarizes various hazards identified between 1978 when Yucca Mountain, located in arid southern Nevada, was first proposed as a potential site and 2008 when the license application to construct a repository for spent nuclear fuel and high-level radioactive waste was submitted. Although advantages of an arid site are many, hazard identification and scenario development have generally recognized fractures in the tuff as important features; climate change, water infiltration and percolation, and an oxidizing environment as important processes; and igneous activity, seismicity, human intrusion, and criticality as important disruptive events to consider at Yucca Mountain. Some of the scientific and technical challenges encountered included a change in the repository design from in-floor emplacement with small packages to in-drift emplacement with large packages without backfill. This change, in turn, increased the importance of igneous and seismic hazards.

1. Introduction

In June 2008, the United States (US) Department of Energy (DOE) submitted, and that September, the Nuclear Regulatory Commission (NRC) docketed the Safety Analysis Report for the License Application (SAR/LA) to construct a repository at Yucca Mountain (YM). Located ~160 km northwest of Las Vegas, Nevada on the Nevada National Security Site (formally known as the Nevada Test Site or NTS), the repository was for disposal of commercial spent nuclear fuel (CSNF), high-level radioactive waste (HLW), and DOE-owned spent nuclear fuel (DSNF) [1,2] (Fig. 1). However in 2010, the Obama Administration and Congress eliminated all funding and brought a practical stop to the Yucca Mountain Project (YMP). Instead, Congress funded DOE to form the *Blue Ribbon Commission on America's Nuclear Future* to review the current policy in the US for storage, processing, and disposal of CSNF, DSNF, and HLW. Recommendations for a new plan were presented to Congress in January 2012 that included a consent-based siting process [3].

As part of this Congressional evaluation, it is useful to identify and understand the scientific and technical issues that YMP faced, in addition to the many social and political conflicts encountered. This paper discusses two tasks of a performance assessment (PA) for geologic disposal at Yucca Mountain: (1) identification of hazards through selection of features, events, and processes (FEPs) and formation of scenario classes from these FEPs; and (2) development of models to evaluate scenario class probability in order to provide a historical perspective on the PA underlying the SAR/LA described in this special issue of *Reliability Engineering and System Safety*. Companion papers describe the site selection, disposal system characterization, and evolution of the modeling system for the YM PA [1,4–10].

For the two tasks discussed, seven PAs serve to demarcate events: (1) a deterministic evaluation of the consequences of igneous disruption in 1982 [11], and a deterministic evaluation of the consequences of the undisturbed behavior in 1984 [12], both of which supported the 1984 draft Environmental Assessment (EA) required by the *Nuclear Waste Policy Act of 1982* (NWPA) and collectively designated as PA–EA; (2) PA-91, the first stochastic PA of both undisturbed behavior and disturbed behavior from igneous and human intrusion [13]; (3) PA-93, also an analysis of undisturbed and disturbed igneous and human intrusion [14, Fig. 1-1]; (4) PA-95, an analysis of only undisturbed behavior [15]; (5) the viability assessment (PA–VA), which examined the influence of igneous and seismic events on undisturbed behavior in 1998 [16]; (6) the site recommendation (PA–SR), an analysis in 2000, which examined undisturbed behavior and igneous intrusion events [17]; and (7) PA–LA, which analyzed undisturbed, early failure, igneous intrusion, and seismic scenario classes and became the basis for SAR/LA [2].

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Fig. 1. View looking south down Solitario Canyon Fault with Yucca Mountain to the east and Lathrop Wells cinder cone to the west ~15 km away from repository boundary.

2. FEP selection and scenario development

2.1. Overview

Any type of analysis must decide what FEPs to model. Here features are objects, structures, or conditions of the disposal system (such as fractures in the host strata), events are natural or anthropogenic phenomena that occur over a short portion of the regulatory period (such as igneous and seismic disruption of the repository), and processes are natural long-term phenomena that occur over a significant portion of the regulatory period (such as water percolation and radionuclide transport through fractures). The event category was common to reliability of analysis in the 1960s and used in the Reactor Safety Study of 1975, which inaugurated large probabilistic risk assessments (PRA) [18]. When the PRA approach was expanded to geologic disposal in 1976 (in conjunction with two separate workshops with earth scientists) [19–21] (Fig. A1), analysis was broadened to include processes. In 1981, the International Atomic Energy Agency (IAEA) formally considered "undetected features" for evaluating the safety of geologic disposal [22]. Because a PA is used in the licensing arena to test compliance with the radiation protection standards promulgated by the Environmental Protection Agency (EPA) (either the generic 40 CFR 191 or the site-specific 40 CFR 197 [1]), the identification and selection of FEPs and formation of scenarios discussed herein is a formal task, and one aspect that sets PA apart from small-scale analysis. Along with the scenario development process, several of the more noteworthy disruptive events identified are discussed. Features and processes associated with the normal evolution of the disposal system are discussed in companion papers on YM models [6–10].

2.1.1. Regulatory criteria for FEP and scenario screening

EPA (in 40 CFR 191 and 40 CFR 197) and NRC (in 10 CFR 63 and the LA review plan) established the general universe of regulatory interest by identifying three criteria to exclude FEPs or scenario classes from the disposal system model [2, vol. 1, Fig. 2.2-1; 23, Fig. 1; 24, Fig. 2] (Fig. 2). One criterion was exclusion of FEPs or scenario classes based on regulatory fiat (e.g., guidance excluding changes in society or technology for inadvertent human intrusion [25, Section 197.15].

A second criterion was exclusion of FEPs or scenario classes based on low probability [25, Section 197.36], via (a) the rationale that a FEP or scenario class was not credible based on site, waste, or repository characteristics (e.g., lack of credible occurrence of tsunami event in the interior of North American continent), or (b) a quantitative demonstration that the probability of occurrence of a FEP or scenario class was less than 10^{-8} in one year (e.g., probability of massive meteor strike $\overline{\wp}\{\mathcal{A}_{meteor}\}$, based on meteor frequencies observed in the past, is $<10^{-8}$ in any year). Prior to 2008, EPA stated the screening probability as 10^{-4} over 10^4 year; in the 2008 amendments, EPA stated it as an annual probability of 10^{-8} (i.e., "those that are estimated to have less than one chance in 100,000,000 per year of occurring" [27, Section 63.342(a)]). The former method emphasized that a FEP probability was estimated over a 10^4 period. The current method emphasizes that the underlying frequency for screening is constant; hence, the probability over 10^4 year is 10^{-4} and over 10^6 year is 10^{-2}.[1]

A third criterion was exclusion of FEPs or scenario classes based on low consequence to the time or magnitude of expected radiological exposure dose ($\overline{D}(t)$) (or cumulative radionuclide releases $\overline{R}$ prior to 2001) (i.e., "…if the expected results of the performance assessments would not be changed significantly in the initial 10,000 year period after disposal." [25, Section 197.36; 27, Section 63.342(a); 28, Section 2.2.1.2.1.3]. This criterion can be met in several ways, for example, (a) a reasoned rationale that inclusion of a FEP would not influence timing or magnitude of dose, (e.g., volcanic eruption far from repository); (b) directly calculating an expected dose from the FEP (i.e., the calculated dose from criticality) and showing that the dose is sufficiently small such that the omission of the FEP does not significantly change the magnitude and time of the resulting radiological total expected dose, or (c) calculating a measure that is indirectly related to dose of the FEP (e.g., a possible future igneous dike feature placed in the travel pathway of radionuclides directs the transport pathway from potential receptors).

A subtle question is whether the basis of the low consequence rationale should use calculations completely separate from the PA analysis and demonstrate exclusion of, for example, the criticality FEP prior to the current iteration of the PA or whether a less straight forward approach is equally valid whereby one makes an hypothesis that a FEP can be screened, conducts the PA, and then verifies that the assumption of exclusion is correct by using specifics of the PA results (e.g., concentrations of fissile material). The advantage of using consequence calculations completely separate from the PA analysis is that the rationale for excluding a FEP may be less ephemeral since they are not tied to a particular PA analysis. Furthermore, this avoids the question of whether the PA analysis is conducted at the proper scale to screen a particular FEP. Hence, a consequence rationale was generally developed separate from the PA for YMP. However, as a counter argument, a consequence rationale to exclude a FEP or scenario classes is always based on the significance of, for example, the estimates of

[1] A subtle difference is that some events, such as early waste container failure, might be treated as independent of time and, thus, would be excluded from the PA using a probability of 10^{-4} over 10^4 year, but would be included in the PA using a probability of 10^{-8} over one year unless the dependence on time was introduced.