Performance Assessments for Design Reviews

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Abstract

This paper discusses the evolution of the design of the potential repository at Yucca Mountain, Nevada, USA, in light of the various postclosure performance assessments conducted to prepare for regulatory reviews of a potential license application. The regulations require that any proposed repository design must meet both long-term performance and operational safety requirements. This paper surveys the evolution of the design of the potential Yucca Mountain repository, especially the engineered barrier system, and discusses the related performance assessments conducted by DOE in support of repository development and NRC in support of developing its capability to review a license application. The survey indicates that DOE design changes correlate well with release or dose-based performance criteria during the earlier part of design evolution. During the latter part, DOE design changes focused more on waste isolation and uncertainty reduction (i.e., strengthening the technical bases). NRC regulations recognize that the design may continue to evolve and performance confirmation information will continue to be collected until repository closure.

1. Introduction

The U.S. Department of Energy (DOE) has studied Yucca Mountain for more than two decades as a potential site for the disposal of high-level radioactive waste. The studies have included site characterization, engineered barrier system design, and performance assessment of the repository system and associated subsystems. Using the outcome of these studies, DOE is expected to submit a license application to construct a repository at the Yucca Mountain site. The U.S. Nuclear Regulatory Commission (NRC) will review any such application. Consistent with the Nuclear Waste Policy Act, NRC has been interacting with DOE during the prelicensing period to resolve outstanding issues so that DOE will be able to submit a high-quality license application, reducing the need for requests for additional information during the licensing review.

Since the initiation of the study of Yucca Mountain as a potential high-level waste disposal site, DOE has revised the proposed repository design several times. The repository design encompasses geotechnical modifications to the natural system (e.g., excavation of tunnels and shafts), emplacement strategies (e.g., layout of and spacing between drifts to not exceed a specified temperature), and engineered structures such as the drip shield, invert, and waste package.

DOE has conducted performance assessments to support repository design development by

(i) estimating the long-term performance of a given design; (ii) comparing the results with the regulatory performance criteria; (iii) estimating performance contributions of design features; (iv) identifying specific proposed design constraints and possible alternative designs; and (v) identifying risk significant design parameters, model development and data needs, and testing needs. Independent assessments by NRC support (i) development of regulations for high-level radioactive waste disposal and (ii) prelicensing interactions with DOE to better understand the DOE approach (e.g., development of risk insights to focus interactions and reviews).

The objectives of this paper are to (i) provide a regulatory context for repository design and performance assessment in the United States, (ii) summarize the evolution of the design of the potential Yucca Mountain repository, and (iii) discuss performance assessments and design evolution. This paper emphasizes the engineered barrier system, especially the waste package. Moreover, it focuses on NRC independent performance assessments and the evolution of the DOE design of the engineered system.

Importantly, the potential licensee (i.e., DOE for Yucca Mountain) is responsible for proposing these designs for the repository and conducting performance analyses to assess the design and demonstrate regulatory compliance. The role of NRC is to independently evaluate the adequacy of the design and compliance demonstration in the context of its regulations.

2. Regulatory Context for Repository Design and Performance Assessment

In 2002, NRC promulgated site-specific regulations in 10 CFR Part 63 for a repository at Yucca Mountain. These regulations reflect NRC emphasis on a risk-informed, performance-based approach to regulation. In this approach, the regulatory decisionmaking process uses risk insights together with other factors such as physical security to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to public health and safety (NRC, 1999).

The regulations require DOE to propose a repository design and conduct a postclosure performance assessment as part of the compliance demonstration of repository safety. Requirements focus on overall system performance. As stated in the regulations, DOE must demonstrate, using performance assessment, that there is a reasonable expectation that, for 10,000 years following disposal, the reasonably maximally exposed individual receives no more than an annual dose of 15 mrem [0.15 mSv] from release of radionuclides from the Yucca Mountain disposal system.[1]

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[1] The State of Nevada and other petitioners challenged both the U.S. Environmental Protection Agency (EPA) standards and the NRC regulations in court. On July 9, 2004, the United States Court of Appeals upheld both EPA standards and NRC regulations on all but one of the issues raised by the petitioners. The court disagreed with the EPA decision to adopt a 10,000-year period for compliance with the individual protection standard and the NRC adoption of that 10,000-year compliance period in the regulations. Thus, the court vacated the EPA rule at 40 CFR Part 197 to the extent that it specified a 10,000-year compliance period and remanded the matter to EPA. In response to the remand, EPA proposed a revised standard, which would provide for a separate dose limit {350 mrem/yr [3.5 mSv/yr]} to be applied beyond 10,000 years up to 1 million years. In response to this change, NRC proposed revisions to 10 CFR Part 63. The proposed rule would implement the EPA proposed standards (EPA, 2005) for doses that could occur after 10,000 years up to 1 million years.

The regulations also require defense-in-depth through at least two barriers to isolate high-level waste—a natural and an engineered barrier. The engineered barrier system must be designed so that it will work with the natural barriers to meet the regulatory limits. Demonstration of compliance requires identifying design features of the engineered barrier system (in addition to natural barrier features) important to waste isolation, taking into account uncertainties in characterizing and modeling the behavior of the barriers. NRC recognizes that there are uncertainties in the isolation capability and performance of engineered barriers. Although the composition and configuration of engineered barrier structures can be characterized more precisely than the natural barriers, NRC recognizes that the experience with complex, engineered structures is limited to only a few hundreds of years. The uncertainties are expected to be accounted for in barrier performance by using ranges of parameter values and/or alternative models in performance assessments.

The regulations also require further evaluations of the design through the performance confirmation program. Should NRC make an affirmative licensing decision, performance confirmation will evaluate the adequacy of assumptions, data, and analyses that led to findings that permitted construction of the repository and subsequent emplacement of high-level waste. Performance confirmation requirements include monitoring key design parameters. NRC regulations recognize that the design may continue to evolve and performance confirmation information will continue to be collected until repository closure.

3. The Evolution of the Potential Yucca Mountain Repository Design

In the late 1980s design, possible emplacement configurations included vertical and horizontal boreholes, short and long boreholes, and filler materials such as chemical buffers or a shielding material. Waste packages (more than 50,000) were thin-walled containers made of metals, ceramics, or composites with a 300-year design life. DOE identified a number of shortcomings, including structural instabilities associated with larger boreholes and the confined space required for maintaining optimum temperature that posed handling difficulties (MacKinnon, 2003; Benton and Connell, 2004).

The 1992 conceptual design focused on easier waste package handling, more stable rock framework by changing to the waste package emplacement configuration from vertical to horizontal, better decay-heat dissipation, longer waste package life (~1,000 years), better access for performance confirmation, and more straightforward performance assessment (Benton and Connell, 2004). The design changes resulted in a larger waste package (21 PWR and 44 BWR) but fewer waste packages (~10,000) being considered for emplacement in horizontal drifts.

The Viability Assessment design of 1998 (DOE, 1998) emphasized prolonged radionuclide containment. The waste package included a 2-cm [~ 0.8-in]-thick inner shell of Ni-based Alloy 22 for corrosion resistance. The design for the inner overpack of the waste package was revised several times: from Alloy 625 to Alloy 825 to Alloy 22. The outer overpack of the waste package was 10.2-cm [4-in]-thick carbon steel (Alloy 516) for structural strength and corrosion allowance. Drip shields were included to protect against dripping water or rock falling on the waste package. Titanium grade 7 plates were proposed for water-diverting surfaces and grade 24 for structural members. DOE justified the use of titanium by stating that a class of alloys different from that of the waste package would protect against systemic failure (MacKinnon, 2003; Benton and Connell, 2004).

The DOE targeted the Site Recommendation design of 2001 (CRWMS M&O, 1999 and 2000; DOE, 2001) to increase corrosion resistance of the waste package, limit groundwater contacting high-level waste, and increase structural strength against rockfall and seismicity. An important design change was to use the corrosion resistant material (Alloy 22) for the outer shell and use nuclear grade 316 stainless steel as the inner shell for structural strength. An extra Alloy 22 lid was incorporated in the design to provide an additional barrier against closure weld corrosion. This design, reversing the location of the Alloy 22, had the benefit of a more corrosion resistant waste package with the structural material mechanically supporting the thinning corrosion-resistant material. The site recommendation design also considered alternative thermal options for repository flexibility: High-Temperature Operating Mode (HTOM) allowing waste package temperature above the boiling point of groundwater and Low-Temperature Operating Mode (LTOM) limiting waste package temperature below the boiling point of groundwater. The same drip shield design as in the viability assessment was to be emplaced just before the repository is closed.

4. Performance Assessments for Various Repository Designs

Independent performance assessments were conducted by the NRC with assistance from the Center for Nuclear Waste Regulatory Analyses using each of the DOE designs chronologically up to the site recommendation design described in the previous section. These analyses were done to support prelicensing interactions between NRC and DOE. Results are consistent with the performance measures in the regulations applicable at the time each design was proposed.

The first two performance assessments conducted by the NRC, referred to here as Iterative Performance Assessment (IPA) Phase 1 (NRC, 1992) and Phase 2 (NRC, 1995), used designs of the late 1980s and 1992, respectively. The performance assessment results from Phase 1 and Phase 2 were expressed as a complementary cumulative distribution function (CCDF) of normalized radionuclide releases, consistent with the release-limit based regulations in 10 CFR Part 60, defined for a generic high-level waste repository. IPA Phase 2 results were significantly different from IPA Phase 1 in scope and approach. Major improvements in IPA Phase 2 over Phase 1 indicate the amount and relative significance of factors that may be influencing the difference. The difference between the CCDF of releases in IPA Phase 1 and Phase 2 analyses primarily resulted from the new consequences and probabilities of processes in the natural system (i.e., pluvial-climate scenario and the addition of the gas pathway for carbon-14 migration in Phase 2). These early performance assessments were conducted by the NRC primarily to demonstrate staff capability to conduct performance assessment analyses.

NRC independent analyses showed a substantial drop in the fraction of the waste package undergoing localized corrosion by transitioning from Alloy 625 to 825, and the transition from Alloy 825 to Alloy 22 showed no localized corrosion failure during the first 10,000 years after repository closure (Dunn, et al., 1999). Performance assessment results for the viability assessment (and later designs) were presented in the form of expected dose, consistent with the NRC regulations in 10 CFR Part 63. Potential concerns with the viability assessment design were identified as fast carbon steel corrosion degrading waste package structural strength, potential stress build-up as a result of the corrosion product accumulating between the shells, and difficulties in achieving long-term cathodic protection by carbon steel.

Independent calculations by NRC using the DOE design for site recommendation showed no corrosion failure during the first 10,000 years after repository closure, under various repository thermal loading strategies. However, the technical bases for supporting the long-term integrity of the waste package and other components of the engineered barrier system are complicated. Examples include the stability of long-term passive film, localized corrosion, microbially influenced corrosion, structural strength, and thermal effects on waste form cladding. Performance assessments continue to play a significant role in evaluating the relevant importance of such factors and their consideration in design.

After Site Recommendation, concerns were raised that the drift may not be stable over long periods, and the drip shield may not be capable of withstanding the load from accumulating rock rubble. DOE then discussed a modified design, increasing the clearance between the drip shield and waste package to minimize waste package–drip shield interaction and reinforcing the bulkhead by adding a flange. Analyses are continuing in this area.

5. Discussions

Consistent with the design optimization theme of this workshop, an attempt was made to discuss DOE’s design evolution and performance assessments. The latter part of the design evolution showed improved waste isolation capability (through, for example, increasing the life of the engineered system) and decreased uncertainty in overall repository performance. In particular, the Viability Assessment design changes to the waste package outer overpack material (i.e., from Alloy 625 to Alloy 825 to Alloy 22) increased the estimated life of the waste package. Switching the inner and outer overpacks of the waste package in the Site Recommendation design resulted in better performance estimates for the waste package. The post Site Recommendation change to the drip shield design (i.e., increasing the clearance between the waste package and the drip shield crown, and reinforcement of the bulkhead) was intended to prevent waste package failure from the drip shield-waste package interaction.

Although design optimization is not a regulatory requirement , the repository developer may optimize design for reasons such as controlling cost, building stakeholder confidence, and providing operational efficiency. If the performance assessment results are used in design optimization, it appears that both the overall system performance measure (i.e., peak expected dose) and the waste isolation capabilities of the engineered and natural systems could be used to maximize the benefits from various iterations of performance assessments as optimization goals.

NRC review does not focus on design optimization but on regulatory compliance. The NRC design review is geared toward identifying engineered components that (i) are significant to repository performance, (ii) could be detrimental to performance of other components, and (iii) are significant to preclosure operational safety.

6. Conclusions

From a regulatory standpoint, any proposed design must meet both long-term performance and operational safety requirements. The survey identified and discussed early design changes and performance assessment results. The design evolution during the latter part of the repository program appears to have increased the waste isolation capability of engineered barrier systems and reduced overall uncertainty. Performance and assessment can be an effective review tool to both evaluate the current design and optimize the design as long as both overall system performance criteria and the waste capabilities of the barriers and uncertainties are considered together. NRC regulations recognize that the design may continue to evolve and performance confirmation information will continue to be collected until repository closure.

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