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Achieving Transparency in the Total System Performance Assessment of a Potential High-Level Radioactive Waste Repository at Yucca Mountain, Nevada

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1. Introduction

As is contemplated in other countries planning to use geologic repositories for disposal of high-level radioactive waste, performance assessment of the long-term behavior of the repository will be a central part of the regulatory decision process in the United States [1]. This central role has raised the importance of the transparency of the performance assessment to outside observers. For example, the U.S. Nuclear Waste Technical Review Board (NWTRB), charged by law with assessing the quality of the scientific and technical work of the U.S. Department of Energy (DOE) on the Yucca Mountain high-level waste repository project, has emphasized the need for transparency in the total system performance assessment (TSPA) of a Yucca Mountain repository [2].

Much of the discussion of transparency involves clarity about what models are used, how they were derived and validated, how they are combined, what data were used as a basis for the parameters, how the parameters were estimated from those data, and what sampling techniques were used for probabilistic analysis. The DOE has undertaken a number of steps to ensure this type of transparency for the Yucca Mountain TSPA. These include use of an independent peer review panel to provide comments and guidance throughout the development of the performance assessment, publication (including availability on the Internet) of the details of the TSPA developed for the viability assessment of Yucca Mountain [3], and the derivation of judgments concerning models and parameters through expert workshops observed by the NWTRB, the U.S. Nuclear Regulatory Commission (NRC), and others.

Another important aspect of transparency is the ability to show clearly how the repository system achieves the projected long-term performance, i.e. what natural and engineered barriers contribute to isolation, and to what extent. Detailed information about the mechanics of the performance assessment might be sufficient to allow other performance assessment experts to understand, and replicate, the analysis. However, this information alone does not necessarily show clearly how the repository system works to protect public health and safety. Indeed, some critics of the use of a total system performance assessment as the basis for regulating repositories have argued that relying on complex mathematical modeling to demonstrate repository performance will not create public confidence in a radioactive waste disposal system [4]. A recent report on nuclear waste management by a Select Committee of the British House of Lords [5] noted advice that "numerical estimates should form only part of the risk evaluation [of a repository] and should be treated with caution because very few people have sufficient understanding of what the numbers represent". On the same point, the report went on to cite comments that "lumping performance parameters together could obscure the significance of a single element which might be critical 'and would not be recognised by someone who did not have a complete grasp of the entire model...and who would?" These comments indicate clearly that more is required than simply presentation of a quantitative calculation of the projected risk from a repository.

Reluctance to place complete reliance on calculations from a performance assessment model was the genesis of the current requirements in NRC regulations for specified levels of performance of individual barriers in a repository -- groundwater travel time, containment in the waste packages, and rate of release from the engineered barrier system [6]. In a proposed draft revision to the repository regulations [1], the NRC staff recognizes that analytical tools have improved substantially in the more than 15 years since the regulations were developed, and that quantitative requirements for specified barriers are no longer needed to supplement the assessment of total system performance. However, they would still require that the repository system use multiple barriers in order to provide "defense-in-depth", and that the analysis of performance evaluate the contribution of those barriers to total performance. The NRC notes that "The proposed requirements will provide for a system of multiple barriers and an understanding of the resiliency of the geologic repository provided by the barriers important to waste isolation to ensure defense-in-depth and increase confidence that the postclosure performance objective will be achieved."

Clearly, transparency of a repository performance assessment requires not only explication of the inner workings of the mathematical models and the data they use, but also analysis showing how the various barriers represented by those models work together to produce the projected performance.

2. "Defense-in-Depth" Approach

DOE is preparing a postclosure safety case to support its upcoming decision regarding site recommendation and possible licensing of a repository system at Yucca Mountain [3]. Quantitative performance assessments are integral to this safety case. However, recognizing that multiple lines of evidence are needed to provide the requisite reasonable assurance that a repository will satisfy regulatory criteria for postclosure performance, DOE will include additional elements in the safety case: design margin and defense-in-depth, consideration of disruptive processes and events, insights from natural and man-made analogues, and a performance confirmation plan. This paper describes an approach to evaluation of one key element of the safety case – defense-in-depth, i.e., use of diverse, redundant barriers against water intrusion and radionuclide movement to mitigate the uncertainties in any of them.

The defense-in-depth approach includes analyses of the contributions of the individual barriers to postclosure performance. These defense-in-depth analyses serve to provide transparency to the performance assessments. Ultimately, this will help communicate the ways in which a repository at Yucca Mountain would protect public health and safety in the long term. In the near term, this increased transparency is playing an important role in refining the design for a potential repository at Yucca Mountain by identifying those aspects of the repository that would benefit most from addition of defense-in-depth measures.

The approach to the defense-in-depth analysis has four steps:

1. Identify principal barriers
2. Assess barriers for common uncertainty and failure mode
3. Conduct barrier neutralization analyses
4. Evaluate overall system defense –in-depth

The first two steps are aimed at identifying those elements of the system that significantly inhibit the movement of water or radionuclides and that should be evaluated to determine the robustness of the system against uncertainties and potential failure modes. The effectiveness of an element is measured in terms of the delay it provides for such movement or the reduction of the rate of transmission through it. For the purposes of this example, a barrier capable of substantially limiting the rate of movement of water or radionuclides through it to less than one part in 10,000 per year or to delay this transmission altogether for 1,000 years is defined as a principal barrier of the system. Principal barriers having common sources of uncertainty or failure are evaluated together as a subsystem rather than separately.

It is the third of these steps that provides the transparency regarding system performance assessment. This step involves barrier "neutralizations," analyses in which appropriate principal barrier subsystems are assumed to be ineffective in inhibiting the movement of water or radionuclides.

The neutralization analyses begin with a TSPA of the repository system. The quantity calculated is the expected annual dose to an average member of the critical population group, the same quantity used to measure postclosure performance of the system. The TSPA calculation of postclosure performance provides the base case for the neutralization analyses. A calculation is then conducted for each defense-in-depth subsystem. In each case, the subsystem at issue is neutralized, i.e., assumed to be in place and effective in all regards except in limiting the movement of water or radionuclides.

The purpose of the neutralization analyses is to determine the contribution of the subsystems of principal barriers to the estimate of postclosure performance. This assessment is different from the sensitivity analyses that will be conducted as part of the TSPA evaluation--in order to determine the maximum theoretical contribution of the barriers to postclosure performance, the performance of the barriers is fully neutralized rather than simply sampled from an estimated probability distribution. The difference in the result for a neutralization calculation from the base-case result provides one measure of the contribution of the neutralized barriers to the base-case results.

3. Application to the VA Reference System

This approach has been applied to the system design that was considered in the Viability Assessment [VA] of a potential repository at Yucca Mountain, Nevada [3]. That design is for a repository in the unsaturated zone at Yucca Mountain. The host rock proposed for the repository is at a height that averages about 250 m above the water table and a depth that averages about 250 m below the surface. In the VA reference system, the waste packages are placed in drifts mined in the host rock. The emplacement drifts are spaced 28 m center to center and the waste packages are located along the centerline of the emplacement drifts at and average spacing of about 17 m.

The VA waste package consists of two concentric, cylindrical metal barriers with accompanying lids (a closed cylinder within a closed cylinder). The inner barrier of the waste package is 2.0 cm thick and made of a corrosion-resistant nickel alloy, Alloy 22. The outer barrier is 10.0 cm thick and made of A516 carbon steel. The outer barrier provides both structural strength and protection to the inner barrier. The outer barrier will corrode slowly over time with little pitting or crevice corrosion and will protect the inner barrier from exposure to oxygen and moisture while it is intact. The analysis also accounts for protection provided by the metal cladding of the ceramic spent fuel pellets.

The repository is assumed to contain 70,000 metric tons of waste. Although a variety of waste forms are to be disposed of, this analysis focuses on the commercial spent nuclear fuel from pressurized water and boiling water reactors that comprises 90 percent of the waste.

In the past, performance assessment sensitivity studies have been used to indicate the principal barriers. These studies show the importance of the waste package and cladding that provide barriers to water reaching the waste, and the waste form, invert, and natural barriers of the system that provide barriers to the mobilization and transport of radionuclides. To illustrate the use of the defense-in-depth methodology, this paper presents the results of neutralization analysis of the following barrier subsystems:

1. Unsaturated zone radionuclide transport barriers
2. Saturated zone radionuclide transport barriers

3. . The combination of unsaturated zone and saturated zone barriers

These examples show clearly the value of redundancy in mitigating the effects of uncertainty in performance of individual barriers.

The results of the neutralization analyses for these barrier subsystems are shown in Figures 1, 2, and 3. The base-case expected performance for the system is shown along with the performance calculated for each neutralization. The expected performance for this particular system design indicates a peak dose rate in the first 10,000 years of about 0.04 mrem/year, well below a reference level of 25 mrem/year. The calculated expected peak dose rate in 1,000,000 years is about 300 mrem/year.

The three neutralization calculations have been conducted applying the same system performance assessment approach used for the base case. Except for the barriers that are neutralized, the models and parameters in each case are the same as those for the base-case analysis. In addition, the models and parameters for the neutralized barriers are the same as in the base case except for those parameters that define the effectiveness with respect to inhibition of movement of water or radionuclides. Other parameters, e.g., thermal properties, are the same.

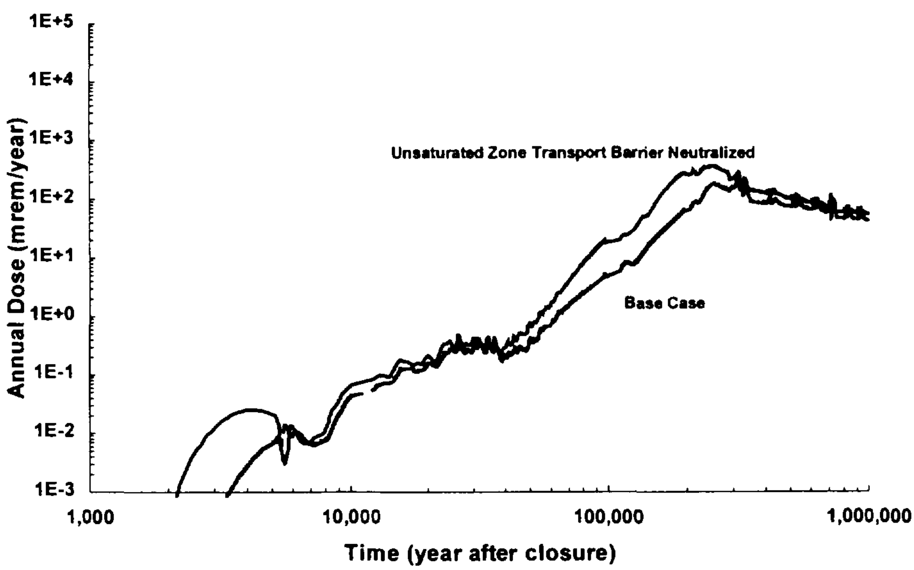

Figure 1. Neutralization of Unsaturated Zone (UZ) of VA Reference System

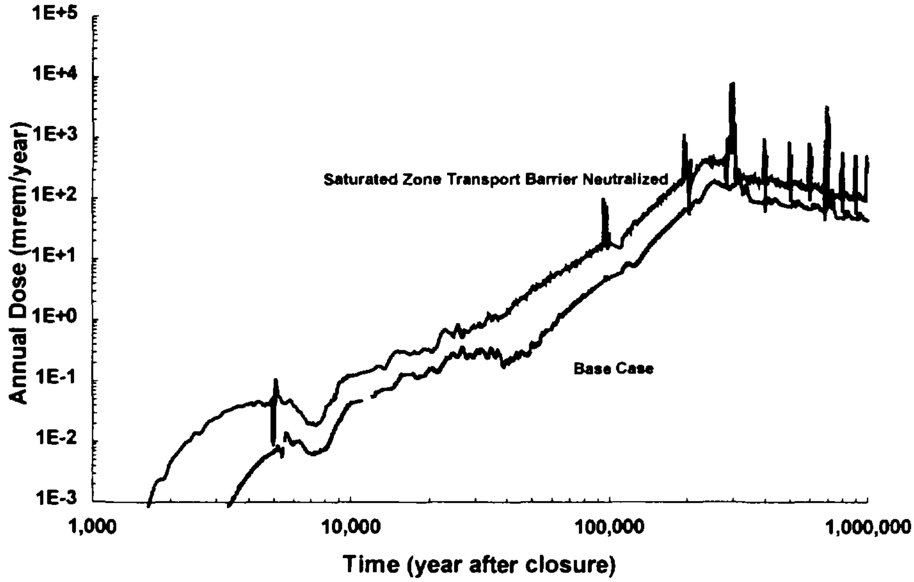

Figure 2. Neutralization of Saturated Zone (SZ) of VA Reference System

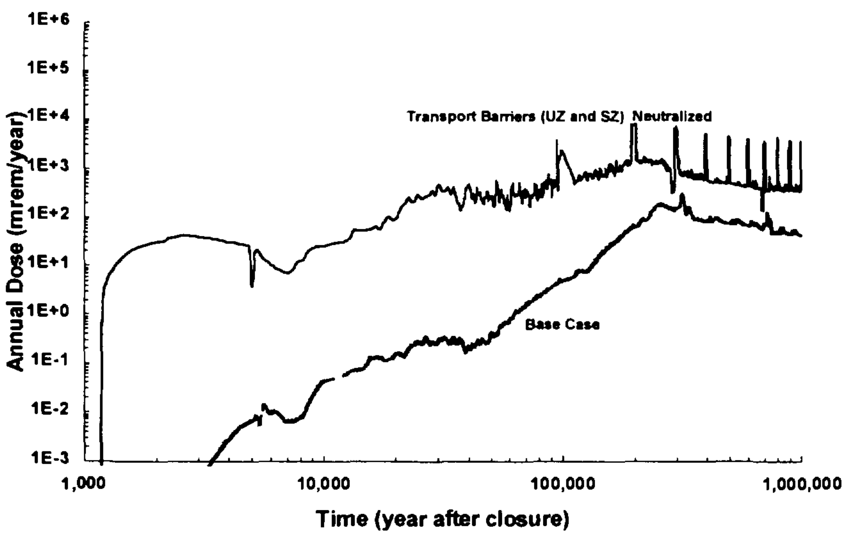

Figure 3. Neutralization of both the Unsaturated Zone (UZ) and the Saturated Zone (SZ) of the VA Reference System

The results for each of these neutralization analyses differ from the base-case results in different ways. The neutralization of the unsaturated zone and saturated zone transport barriers individually show only minor changes from the base case. Radionuclides released from the waste package are affected in both of these barrier subsystems so that failure of one of them is compensated by good performance in the other. The importance of the redundancy in these barrier subsystems is shown when they are both neutralized at the same time. The fact that these subsystems are redundant means that uncertainties in each of them are reduced in importance. An issue high-lighted by these analyses is the uncertainty in the conceptual model for transport that is common to both of these barriers. Consequently, it appears desirable either to ensure that the uncertainties in this model are small or to mitigate their effects.

These analyses demonstrate an important aspect of the concept of defense-in-depth. In the sense of system sensitivity, a small difference between a neutralization analysis and the base-case performance might appear to suggest that the neutralized barrier is not important. However, redundancy in the barriers is important to performance in the broader sense--enhancement in confidence regarding system performance. Neutralization of a barrier that is fully backed up by another will show little difference compared to the base-case performance, yet that barrier plays an important role in that it backs up the other. The barriers work together to enhance system performance.

4. Summary

This paper has presented an approach to quantitative assessment of the degree of postclosure defense-in-depth provided by the reference system of the VA. This approach (1) identifies principal barriers, (2) assesses barriers for common uncertainty and failure mode, (3) conducts barrier neutralization analyses, and (4) evaluates overall defense-in-depth. The neutralization approach of step 3 is particularly useful in untangling the contributions of various barriers to the results calculated by performance assessments. In fact, it provides the only way of assessing the contribution of barriers that are fully redundant with one another.

The approach has been applied to the VA reference system. It shows how the natural transport barriers contribute to performance of the system. Since their individual contributions are redundant, uncertainties in those individual contributions are reduced in importance. The analyses also suggest uncertainties common to both of these barriers are important to the safety assessment. Thus, the approach appears to be capable of determining the contribution of the principal barriers to system performance.

The ability to use performance assessment to show not only how the repository system is expected to perform, but also how it achieves that performance, should contribute substantially towards providing needed transparency to the safety case for a geologic repository. It is also a valuable tool during the development of the repository design and associated safety case, by identifying areas in which performance would be enhanced by increased redundancy (through addition of an engineered barrier, or reduction of uncertainty about a natural one).

References

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