USE OF PERFORMANCE ASSESSMENT INFORMATION TO EVALUATE ALTERNATIVE YUCCA MOUNTAIN PERFORMANCE STANDARDS

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ABSTRACT
The continuing advance of scientific knowledge and the evolution of performance assessment capabilities for the proposed spent fuel and HLW repository at Yucca Mountain have resulted in the means to evaluate the appropriateness of Yucca Mountain performance regulations. This paper provides some examples of how performance assessment information has been used to evaluate Yucca Mountain regulations as well as a description of how regulatory thinking has been influenced by these performance assessments.

BACKGROUND
Regulations governing the performance of geologic repositories for the disposal of spent fuel and HLW in the US have evolved for more than 20 years. Regulations governing site selection and radiological health and safety were developed by both the US Nuclear Regulatory Commission (NRC) and the US Environmental Protection Agency (EPA). The technical criteria in NRC’s 10 CFR Part 60 were first promulgated in 1983 (1). Part 60 contains a series of prescriptive, quantitative criteria on a variety of components of a geologic repository system. For example, NRC provided quantitative limits on: minimum groundwater travel time from the engineered barriers (assumed near the disposed waste itself) to the accessible environment; maximum release rates from the engineered barriers, and maximum radionuclide cumulative releases into the accessible environment. The US Department of Energy (DOE) issued siting guidelines consistent with Part 60, 10 CFR Part 960. DOE intended, in Part 960, to make a series of ‘higher level findings’ that they would have high confidence that each and every aspect of Part 60 can be complied with at a particular site during the site selection process.

In 1985 the EPA promulgated 40 CFR Part 191 (2) as a generally applicable environmental standard for deep geological disposal. The EPA Part 191 standard has three parts: (1) a set of release limits for radionuclides proceeding into the accessible environment; (2) an individual protection standard in terms of millirem per year; and (3) a groundwater protection standard in terms of maximum radionuclide concentrations in potable drinking water. What set apart the Part 191 standard from Part 60 was that EPA performed a rudimentary set of ‘back calculations’ in order to establish what EPA felt were appropriate release limits based on an established starting policy of the maximum allowable human health consequence (3). These back calculations were based on assumptions about a generic repository rather than any specific site.

At the time these detailed criteria were promulgated and implemented in the early 1980s there was only a general knowledge about the relative importance of each criterion with respect to their importance in protecting human health. The situation is different now in two important
respects. First, specific repository sites have been identified. The WIPP site in New Mexico has been licensed for disposal of TRU wastes, and the Yucca Mountain site in Nevada is currently under study for use as a spent fuel and HLW repository. Second, the field of total system performance assessment (TSPA) has matured tremendously. The path toward development of a truly total system performance assessment using a probabilistic approach began over ten years ago. EPRI has been involved in some of the earliest efforts. EPRI produced the first Yucca Mountain TSPA using an integrated, probabilistic approach in 1990 (4). Using such an approach it was possible to evaluate the relative importance of various components of the Yucca Mountain system in protecting human health. Since 1990 several TSPAs have been produced for or by DOE (5-9), EPRI (10-13), and the NRC (14,15). During the course of all of these TSPAs much has been learned about not only Yucca Mountain itself, but how to assemble TSPAs and use them to gain insight on important repository system features and interactions.

Insight from the conduct of TSPAs can also be used to evaluate the appropriateness of various possible performance standards. EPRI has made use of its own TSPAs in this fashion for many years. EPRI used TSPAs to evaluate the appropriateness of Part 191 for application specifically to Yucca Mountain (11), and aspects of later TSPAs (12,13) to provide input to the Nuclear Energy Institute (NEI) for use in NEI’s comments on the recent draft NRC (16) and EPA (17) regulations for Yucca Mountain. The purpose of this paper is to provide some brief examples of how insights gained in the conduct of TSPAs for the candidate Yucca Mountain site have been used by EPRI to evaluate the appropriateness of alternative Yucca Mountain standards. The work here draws on many of the TSPAs conducted not only by EPRI, but also by DOE and NRC. The paper concludes with a discussion of how the advances in TSPA capabilities and information influenced regulatory thinking.

MAJOR COMPONENTS OF STANDARDS FOR WHICH TSPA CAN PROVIDE INSIGHT

There are several major components of a potential performance standard for which TSPAs can be used to evaluate their appropriateness and/or effectiveness. Examples of these are:

- **Subsystem performance criteria**: TSPA can be used to evaluate the relative importance of various subsystems, such as container failure times and rates, engineered barrier system (EBS) release rates, groundwater travel times, groundwater concentrations, and radionuclide fluxes into the biosphere. If multiple subsystem performance criteria are set, TSPA can be used to evaluate which particular criterion is most limiting under particular conditions. It is also possible that one subsystem criterion may be in conflict with another in the sense that attempts to optimize repository design to comply with one subsystem criterion may cause non-compliance with another subsystem criterion.

- **Time period over which the regulation is in effect**: TSPA can be used to evaluate the effect of changes in uncertainty with time or the time in the future at which certain events or scenarios become more or less important to performance. They can also be used to examine estimated risk or dose over time. All three of these uses provide valuable insight in establishing an appropriate time period of regulatory control.

- **Alternative critical or other exposure group assumptions**: All US regulations governing deep geologic disposal include individual dose limits. What varies between the regulations are the assumptions about the characteristics of the individuals, real or hypothetical, for whom the dose projections are being made.
Alternative indicators of performance: Alternative performance assessment analysis can provide insight into, for example, the relative importance of various components of the repository system in reducing the health hazard of the disposed HLW. This can aid in demonstrating the existence of multiple barriers that contribute substantially to overall performance.

In addition, there are other aspects to regulatory compliance for which TSPAs can be useful. For example, TSPAs can provide additional regulatory confidence. Confidence can be enhanced in a multitude of ways. Fully exploring the uncertainties in the analyses is an obvious way of enhancing confidence. TSPAs can be used to analyze the presence of and relative importance of multiple barriers to the release and transport of radionuclides. Demonstration of multiple barriers, including DOE’s confidence in each barrier (expressed using uncertainties both quantitative and qualitative) would be required in NRC’s draft Part 63 regulation (16).

There are certainly aspects of evaluating a potential regulation for which TSPA is not suited. Aspects of the regulation that are policy decisions, such as the specific value of a dose or risk limit, are not generally appropriate to evaluate using TSPA. An exception to this would be if multiple policy decisions result in multiple, and potentially conflicting criteria. As pointed out earlier, TSPA could then be used to investigate under which conditions which criterion would be most limiting and if the multiple criteria are in conflict. Legal precedents are also particularly immune from TSPA.

As discussed above, the Part 191 release limit was based on a performance assessment back calculation for a generic repository. In a report prepared for the National Academy of Sciences (NAS) Committee on the Technical Bases for Yucca Mountain Standards (TYMS Committee), EPRI conducted TSPA analyses for the purpose of evaluating the appropriateness of Part 191 as a Yucca Mountain-specific regulation, and to suggest alternatives as appropriate (11). The NAS TYMS Committee was tasked by Congress to make recommendations to EPA on the technical bases for EPA’s Yucca Mountain-specific standard, 40 CFR Part 197 (17).

The following sections provide brief examples of some of the analyses conducted to evaluate some of the issues surrounding alternative Yucca Mountain regulations described above.

SUBSYSTEM PERFORMANCE CRITERIA

It is assumed that the goal of any regulation governing the disposal of waste is to protect present and future human populations from adverse health consequences. Regulatory criteria that directly address human health, such as health risk (or absorbed dose if one assumes the linear, no threshold hypothesis relating dose to cancer risk) limits are considered overall performance criteria. Such criteria require an evaluation of the total repository system performance.

Subsystem criteria impose constraints on the performance of some component of the total system, such as the EBS or groundwater. NRC proposed such subsystem criteria for Part 60 in an era when they felt they needed additional confidence in many of the subsystems and when they had little confidence in performance assessment. The following sections discuss some of these subsystem criteria and provide examples of TSPA information that has been used to suggest difficulties with them.
Groundwater Travel Time (GWTT)

Part 60 has a minimum 1,000-year GWTT limit for groundwater from the edge of the ‘disturbed zone’ to the accessible environment (defined as 5km downstream). Although 1,000 years is long compared to the half-lives of some of the important fission products, such as Cs-137 and Sr-90, all recent performance assessments have found that Tc-99, I-129, and Np-237 generally contribute the greatest doses to downstream individuals. All three of these latter radionuclides have half-lives at least two orders of magnitude larger than 1,000 years making a 1,000-year GWTT requirement ineffectual.

Performance assessment analyses conducted by the M&O (DOE’s contractor) have shown that there is some groundwater beneath Yucca Mountain that may have travel times less than 1,000 years. However, the amount of groundwater involved in this relatively fast flow was also determined to be small enough that no significant amount of radioactivity could be transported along this pathway (e.g., 8). This analysis was instrumental in causing NRC to propose elimination of the GWTT requirement at Yucca Mountain in its recent proposed regulation, 10 CFR 63 (16).

Release versus dose

The EPA standard 40 CFR Part 191 (2) contains a cumulative release and an individual dose rate limitation. In EPRI’s 1994 report to the NAS TYMS Committee (11), EPRI noted there were several components in EPA’s model for a generic site that were considerably different than the specifics for Yucca Mountain. For example, the EPA model included transport of the radionuclides from the generic site into a world river from which considerable use of the river water was assumed (3). In the case of Yucca Mountain no such river exists. Thus, the allowable release rates based on an upper limit of health consequences would have to be recalculated for Yucca Mountain. Furthermore, advances in knowledge about Yucca Mountain would also require additional modifications to release limits to keep the release limits consistent with EPA’s starting policy of the maximum number of allowable health consequences (3). Such continual change in the regulations is impractical. Rather, a direct use of health-based criteria, in the regulation (dose or health risk limitations) is preferable (11).

Another aspect of the release versus dose rate criterion question is the difference in the relationship of release and dose to groundwater flux. In general, both the EPRI and DOE models find that EBS release rates increase with increasing flux through the repository horizon (see, for example, 9,11). Since the EPA release rate criterion limits releases past a downstream position of 5km during the first 10,000 years higher groundwater fluxes and groundwater velocities will result in higher 10,000-year release rates. However, dose rates to a critical group or a maximally exposed individual (MEI) are found to have either only a weak or sometimes even an inverse relationship to groundwater flux. The 1994 EPRI analyses showed a slightly inverse relationship to saturated zone flow velocity since a slight increase in saturated zone dilution was assumed to occur at the higher flow velocity (11).

Furthermore, it is required that the critical group and MEI be associated with the highest concentrations in the saturated zone (16-18). Yet the way radionuclide concentrations entering the saturated zone from the unsaturated zone are modeled by DOE and EPRI results in lower radionuclide concentrations as the groundwater flux through the unsaturated zone increases.
This is because it is assumed that all radionuclides emanating from the repository horizon are thoroughly mixed by the time they enter the saturated zone. While such an assumption may be overly optimistic, especially for higher flux rates, additional analysis conducted by EPRI (13) suggests there will be very little difference in saturated zone concentrations 5+ km downstream for a range of unsaturated zone flux rates. The analysis is based on the fact that more dispersion in the saturated zone will occur if the original source area entering the saturated zone is smaller. Therefore, if there is actually less mixing in the unsaturated zone, causing a smaller, more highly concentrated plume entering the saturated zone, there will be relatively more mixing in the saturated zone. The end result is that critical group or MEI dose rates are much less sensitive to groundwater flux rates than are release rates. This has implications for the relative importance of quantifying groundwater fluxes.

**Maximum concentration limits (MCL’s)**

Both the existing EPA standard, Part 191, and the draft EPA standard for Yucca Mountain, Part 197, contain limitations on radionuclide concentrations in potable groundwater (commonly referred to as Maximum Concentration Limits – MCLs). The only application of the existing Part 191 to-date has been at the WIPP site in New Mexico. The WIPP site, unlike the Yucca Mountain site, has no potable groundwater. Thus, the MCL provision in Part 191 has not yet been exercised.

In a preliminary effort to assess the potential environmental benefit of the imposition of the Part 191 or draft Part 197 MCLs at Yucca Mountain, the author conducted a brief review of DOE’s Draft Environmental Impact assessment for Yucca Mountain (19). While the DEIS performance assessment does not directly assess the environmental benefit of including a groundwater protection clause in the performance standard, some of the information provided can be used for this purpose. It should be noted that possibly different levels of conservatism exist in the different environmental impact assessments DOE performed.

The following assumptions were used by the author to assess the relative environmental benefits of including or excluding a groundwater protection clause:

- DOE may choose to alter the repository design specifically to lower groundwater concentrations;
- Groundwater concentrations could be lowered if the disposed spent fuel and HLW were distributed over a wider area. Distributing the waste over a wider area effectively dilutes the released waste as it enters the groundwater.
- The DEIS considers ‘high’ and ‘low’ thermal loading design alternatives. The ‘high’ loading design concentrates the disposed waste into a smaller area than the ‘low’ loading design. Thus, one would expect the ‘low’ thermal loading design to result in lower groundwater concentrations than the ‘high’ loading design.
- The measures of “environmental impact” considered were related to individual and population doses due to the construction, operation, and 10,000-year post-closure periods due to the release of radionuclides from the disposed waste as well as the natural radionuclides released due to the excavation of the repository. Information DOE presented in the DEIS related to impacts on workers, non-human biota, or other socio-economic costs were not considered by the author in the following analysis. Other than the disposal of spent fuel and
HLW in Yucca Mountain, it was assumed no other component of the radioactive waste management system would impact groundwater significantly.

The DEIS provides the following relevant quantitative results of their analyses related to individual and population doses or latent fatalities:

<table>
<thead>
<tr>
<th>Impact type</th>
<th>‘High’ thermal loading design</th>
<th>‘Low’ thermal loading design</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak annual individual dose via groundwater in 10,000 years</td>
<td>0.32 mrem</td>
<td>0.13 mrem</td>
<td>Radionuclides released from the disposed waste into the groundwater – 5km downstream</td>
</tr>
<tr>
<td>Population dose via groundwater integrated over 10,000 years</td>
<td>0.37 person rem</td>
<td>0.27 person-rem</td>
<td>Radionuclides released from the disposed waste into the groundwater</td>
</tr>
<tr>
<td>Latent cancer fatalities via groundwater in the local population integrated over 10,000 years</td>
<td>0.00019</td>
<td>0.00014</td>
<td>Radionuclides released from the disposed waste into the groundwater (using the numbers above and a conversion factor of 0.0005 latent cancer fatalities per person-rem)</td>
</tr>
<tr>
<td>Peak average annual individual dose (via the air pathway) during repository operations prior to closure</td>
<td>0.49 mrem</td>
<td>1.8 mrem</td>
<td>Short-term (100 year) impact due to natural Rn-222 released from the excavated rock and tunnels during construction, loading, and monitoring</td>
</tr>
<tr>
<td>Latent cancer fatalities via the air pathway in the surrounding population integrated over the first 100 years</td>
<td>0.14</td>
<td>0.41</td>
<td>Short-term (100 year) impact due to natural Rn-222 released from the excavated rock and tunnels during construction, loading, and monitoring – via air pathway</td>
</tr>
</tbody>
</table>

The above DEIS analyses confirm that the individual dose rates due to release of radionuclides into the groundwater are higher for the ‘high’ thermal loading design. Thus, spreading out the waste into more tunnels and over a larger area does seem to lower individual doses from the groundwater pathway. Since these individual doses are directly correlated to groundwater concentration for releases to groundwater, the ‘low’ thermal loading design would appear to have the lower environmental impact in terms of individual dose. There appears to be very little difference in population dose or latent cancer fatalities integrated over 10,000 years due to groundwater contamination, however, between the two thermal loading designs.

The DEIS suggests that most of the radiological risk is not due to very long-term releases to the groundwater. Rather, it is due to the relatively short term gaseous release of Rn-222 during construction, loading, and monitoring. Because more rock is excavated and more tunnels are used for the ‘low’ thermal loading design, the ‘low’ loading design results in higher environmental impact than the ‘high’ thermal loading design.
Thus, if EPA imposes a groundwater protection requirement it may cause DOE to choose a design that, while reducing groundwater concentrations, would cause the overall environmental impact to be higher than if simply an individual protection standard were used. While a ‘low’ thermal loading design could reduce groundwater concentrations somewhat, leading to a trivially small reduction in health impacts via the groundwater pathway, the potential health impacts in the short term would actually be relatively much higher for the ‘low’ loading design via the gaseous pathway. Furthermore, the groundwater protection clause trades a decrease in environmental impacts over the very long term for a larger increase in short term impacts.

Thus, the imposition of a groundwater protection clause in the EPA draft standard may be viewed as a detriment to minimizing environmental impact, rather than the reverse. Because the individual protection clause applies to all potential pathways (groundwater and gaseous), the individual protection clause – by itself - provides a more robust control on appropriate repository design.

TIME PERIOD

There are several ways TSPAs can be used to evaluate the time frame over which a regulation for Yucca Mountain should remain in effect. One is to look at the time periods over which various components of the Yucca Mountain system become increasingly uncertain. In general, the following list of components are more certain over the indicated time periods (20):

- $10^{1-2}$ years: stability of present-day human behavior
- $10^2$ years: post-closure monitoring timescales (both LLW and HLW)
- $10^{2-4}$ years: ecosystem stability
- $10^{3-4}$ years: climate stability
- $\sim 10^6$ years: deep disposal peak dose; geosphere stability

One may wish to adopt a “weakest link” approach for the regulatory time period (20). This approach suggests that the regulatory time period be limited to that of the component the TSPA analyses suggests is important to repository performance since an increase in uncertainty in that component should lead to the earliest increase in uncertainty in overall repository behavior. Another potential time period would be when the “expected value” from a TSPA begins to lose its ‘lay’ meaning (20). That is, the public may consider an “expected value” to mean the outcome is likely to be near this particular value. This may correspond to the existence of a distinct ‘mode’ in the distribution. When uncertainties have increased to the point where any value, be it the mode or “expected” (mean) value simply represents one particular value of a very broad distribution, then this could be a time at which the compliance period would end. This does not mean that analyses beyond this period are useless. Rather, such very long-term analyses can still be used to provide semi-quantitative insight even if direct use of the quantitative results should be avoided. EPA recognized this in their draft Part 197 regulation in that they ask for analyses beyond the 10,000-year time period (over which the quantitative limit applies), but stated that such analyses should not be used for quantitative compliance purposes (17).
In the case of Yucca Mountain, all EPRI, DOE, and NRC performance assessments find that the amount of water percolating through the system is one of the most important factors. Since climate is one of the most important drivers for groundwater flux rates, the time period over which present-day climate is considered reasonably stable could, and is often used as the primary basis for regulators in setting the time period for the regulation. DOE’s TSPA-VA (9) indicated that the ‘seepage fraction’ (fraction of containers assumed to have groundwater dripping on them) and the uncertainty in the seepage fraction increases rapidly when the groundwater percolation rate rises above about 10 mm/yr. Since they considered the present-day climate to be delivering approximately 10 mm/yr at the repository horizon, the time at which the climate became wetter will result in more uncertainty in the seepage fraction.

The presence of heat due to emplacement of spent fuel is also commonly considered to increase uncertainty in all performance assessments for Yucca Mountain, even if the amount of uncertainty is not well defined. The time period over which the greatest amount of thermal disturbance occurs is in the $10^{1-2}$ year range (e.g., 9,13). One could argue that uncertainties due to thermal effects should decrease after that time period.

There are also other subsystem components that could, and have been investigated regarding their uncertainty versus time. Analyses associated with TSPA-VA by DOE suggests that chemical stability is uncertain for time periods on the order of $10^{2-4}$ years. Hydraulic variability is connected to both natural variability and thermal effects. DOE analyses of the container corrosion behavior versus time indicates that both the fraction failed, and the individual dose rate as a function of the fraction failed become increasingly uncertain after about $10^3$ years (9). Earlier EPRI analyses also suggest about $10^3$ years is when container failure fractions become increasingly uncertain (12).

Thus, it appears that, based on existing knowledge, $10^{2-4}$ years is an appropriate time period for a Yucca Mountain regulation if one wants to avoid major increases in uncertainty. Future research, however, may provide sufficient information to fundamentally alter the amount of uncertainty in future system behavior to prompt a change in the appropriate time period.

ALTERNATIVE MEASURES OF PERFORMANCE

There are many other ways to indicate repository performance for which TSPAs can provide insight for alternative regulations. In addition to showing performance of particular barriers, one can examine the ability of individual barriers to reduce theoretical doses, examine alternative exposure groups and biospheres, compare to ore bodies and natural concentrations and fluxes. All of these alternatives were demonstrated in EPRI’s most recent Yucca Mountain performance assessment (13). EPRI provided analyses to examine the relative quantitative behavior of ten system features. The analysis, which space does not permit to include in this paper, provided confidence that the NRC requirement in draft Part 63 that DOE take credit for at least two ‘barriers’ in the Yucca Mountain system is both reasonable and demonstrable.

Other analyses in (13) examined the dose distribution in the local population due to differences in diet, and alternative biosphere scenarios. These helped provide insight into the appropriateness of the draft Parts 63 and 197 with respect to their definitions of critical group or MEI, respectively, along with their general discussion about the biosphere assumptions that have
to be made. The result of the analysis suggested that there is not a great deal of difference in the application of either the NRC critical group or the EPA MEI approach in actual application, although there is more international precedent for the use of a critical group approach suggested by NRC (21).

**INFLUENCE OF TSPA EVOLUTION ON REGULATORY THINKING**

TSPAs can, and already have provided a considerable amount of insight into the appropriateness of particular performance regulations. The maturation of the TSPA field applied to Yucca Mountain in shaping the performance standard for Yucca Mountain has been specifically recognized by NRC. The following are a few quotes from the Background section of the draft Part 63 (16) that provide the reasons why NRC has eliminated subsystem performance criteria in favor of an overall performance standard:

> It should be noted that during the late 1970s and early 1980s, when the Commission was first considering the development of proposed technical criteria for geologic repositories, quantitative techniques for assessing repository performance were in their infancy. The lack of experience with, and confidence in, quantitative methods for addressing the uncertainties associated with estimates of repository performance weighed heavily as the Commission considered options for formulating generic regulations for HLW disposal. …[T]he Commission now believes that the application of such methods has matured sufficiently to move away from its earlier approach.

> Identification of … subsystem performance measures was expected to be helpful input to DOE’s design process, without being overly restrictive. It is now recognized that NRC attempted to define such criteria on the basis of limited, existing knowledge, without benefit of research and site-specific information that only later was acquired during characterization of a specific site at Yucca Mountain.

> Upon review of this regulatory history, the Commission is persuaded that much of the basis for NRC’s initial development of the specific numerical values for the subsystem criteria was generic judgment with regard to what was (and was not) feasible with regard to the quantitative assessment of long-term repository performance. … Furthermore, after 15 years of experience in working with the requirements of Part 60, the Commission is concerned that, for the Yucca Mountain site, the application of the subsystem performance criteria at § 60.113 may impose significant additional expenditure of resources on the nation’s HLW program, without producing any commensurate increase in the protection of public health and safety.

> The Commission believes that application of a single, all-pathway standard is protective of public health and safety, and obviates the need for separate, single pathway limits.

> The Commission also recognizes, and believes, it is important to acknowledge that experience and improvements in the technology of performance assessment, acquired over more than 15 years, now provide significantly greater confidence in the technical ability to assess comprehensively overall repository performance, and to address and quantify the corresponding uncertainty.

Thus, NRC has found that the continued evolution in TSPA capability has allowed a fundamental change in the nature of their draft regulation for Yucca Mountain.
CONCLUSION

Advances in the field of total system performance assessment have provided a vehicle for significant insight into the appropriateness of the existing and proposed regulations governing deep geologic disposal of radioactive waste for the candidate HLW repository at Yucca Mountain. A review of some of that insight was presented above. Examples of how certain subsystem performance criteria were ineffectual (GWTT), or counterproductive to overall human health (MCLs) were provided. The potential bases for selecting the time period of compliance was discussed; an appropriate time period of compliance may be on the order of $10^{2-4}$ years. Alternative performance indicators were also shown to provide additional insight into repository performance that can play a role in the regulatory process.

EPRI’s TSPA analyses to-date support the NRC approach: the use of a single, overall performance standard and the elimination of specific, quantitative subsystem requirements. This does not mean to imply that further R&D in support of particular subsystems is no longer needed. Rather, an overall performance requirement provides DOE the freedom to use their resources on those components of the system most important to protecting public health. The development of the field of TSPA has allowed this to occur.

REFERENCES


