Standards & Regulations for the Geologic Disposal of Spent Nuclear Fuel and High-Level Waste

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Summary & Recommendations

This paper draws on my experience as a reviewer of the scientific programs and performance assessments of the geological repository for transuranic waste at the Waste Isolation Pilot Plant in New Mexico and the proposed repository for spent nuclear fuel and high-level waste at Yucca Mountain in Nevada. In addition, I have served on numerous committees of the National Research Council that have addressed many aspects of nuclear waste management. These comments and recommendations focus on standards and regulations for licensing a geological repository for SNF and HLW; however, I have added a brief annex on the classification of nuclear wastes. The initial classification of the waste determines the disposal strategy: deep geological disposal *vs.* near surface disposal. In this paper, I present the basis for the following recommendations:

- The standard and supporting regulations for the licensing of a geologic repository should be *generic* - applicable to all potential sites. These standards and regulations should be finalized prior to the site-selection process.

- Site-selection should be based on a set of common-sense criteria (*e.g.,* NRC, 1978). If during site characterization it is discovered that the site does not meet the technical criteria, then it should be abandoned. These criteria should not only consider the characteristics of the site, but should also include careful consideration of the degree to which a site can be analyzed. Unnecessary complexity can jeopardize the confidence in the analysis of a suitable site.

- The standard must acknowledge and adapt its structure and standard-of-proof to the fact that there are two time-scales of interest: the human time-scale that extends to some thousands of years and the geologic time-scale that extends to many hundreds of thousands of years. Reasonable and robust containment at both time scales is possible, but the type of analysis and standard-of-proof will be different for each.

- Because there are two time-scales and because the types of "proof" for each are very different, the total system analysis of performance, reduced to a single numerical estimate of risk at some very distant time, should be abandoned. The standard should not require scientists and engineers to complete an analysis that is at its best opaque and at its worst not believable.

At the end of this paper, I have provided a short list of references that are not meant to be comprehensive, but rather were selected because they provide an expanded discussion of some of the critical points in this paper.

1. Introduction

The standards and regulations for the management, transportation and disposal of radioactive materials have been key to the development of strategies for the handling and disposing of radioactive materials at the "back-end" of the nuclear fuel cycle. This white paper focuses on issues relevant to the disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) from reprocessing and summarizes previous U.S. experience in the attempt to develop a standard and regulations for the geologic disposal of these wastes.

As the nation reconsiders its strategies for an expanded role for nuclear power and in light of the failed effort to establish a geologic repository for SNF and HLW, the United States has an opportunity to learn from our experience of the past thirty years. This experience is not only with the development (or failure to develop) standards and regulations, but also there has been a substantial advance in our knowledge and understanding of the science of the relevant geologic processes (*e.g.,* geochemistry and contaminant transport) and specifically of the behavior and fate of radionuclides in the geosphere. We can also benefit from the sobering reality of how difficult it is to project the future behavior of a geologic repository over extended spatial and temporal scales that stretch for tens of kilometers and out to a million years.

The main purpose of a standard and its implementing regulations should be to protect human health and the environment, but ***the structure of the standard and regulations, as well as the standard-of-proof for compliance, should not extend beyond what is scientifically possible and reasonable.*** The demonstration of compliance must not only be compelling, but it must also be able to sustain scientific and public scrutiny.

Finally, any determination of compliance will involve uncertainty. This uncertainty is best managed by the proper location and design of the repository, but there will always be uncertainty in the analysis that is the basis for the determination of compliance. ***This uncertainty must be considered in developing a standard and implementing regulations.***

1.1 History

The regulatory history for nuclear waste stretches back nearly 40 years to the founding of the Nuclear Regulatory Commission in 1974, partially in response to growing realization of the challenge managing radioactive waste and the controversy and failure to develop a geologic repository in a salt mine near Lyons, Kansas. The Nuclear Waste Policy Act of 1982 (see Carter, 1986, for a summary of the legislative process) defined the roles of the principal government agencies: Environmental Protection Agency would set the standard to protect public health and the environment; Nuclear Regulatory Commission would establish license requirements and implementing

regulations and license the repository; Department of Energy would determine the suitability of the site, submit the license application and, if approved, operate the facility. In 1982, the expectation and legal requirement was that DOE would take possession of spent nuclear fuel for the purpose of disposal in a geologic repository by 1998. The NWPA of 1982 required that multiple sites, finally in salt, tuff and basalt, be investigated in parallel, with the final selection based on a comparison of the performance of the sites.

Following a tortuous path, lasting over 26 years, the EPA issued the final site-specific Yucca Mountain Standard (10 CFR 63) on September 30, 2008, some months after DOE had submitted the license application for Yucca Mountain on June 3, 2008. During those 26 years, the NRC promulgated high-level waste disposal regulations (10 CFR Part 60 in 1983); EPA set generally applicable environmental standards (40 CFR Part 191 in 1985) and the DOE established guidelines for site suitability (10 CFR 960 in 1984). It is important to note that in Part 60, NRC emphasized a series of subsystem requirements most directly related to groundwater travel time and the waste form and its packaging (*e.g.,* metal canister and backfill). The subsystem requirements for the waste package were considered to be important because geologic isolation alone was not sufficient guarantee of safety (Walker, 2000, pp. 165-166). The waste form and packaging materials had a specific performance requirement in that they had to provide "substantially complete" containment during the first 1,000 years with a minimum waste package lifetime of 300 to 1,000 years, gradual release from the engineered barrier system (minimum rate of 1 part in 100,000 per year), and the slow release from the engineered barrier system to the accessible environment (*e.g.,* ground water travel time of at least 1,000 years). In the absence of Yucca Mountain as a repository, the site specific regulation, Part 63, has no further applicability, but Part 60, with the generic requirements, remains in force. In 1987, a federal court remanded the EPA standard because it was not consistent with existing environmental laws, mainly the Clean Water Act of 1972. During that same year, 1987, Congress amended the NWPA, selecting Yucca Mountain as the only site to be characterized.

Five years later, the Energy Policy Act of 1992 directed EPA to establish a site-specific standard for Yucca Mountain based upon and consistent with recommendations from the National Academy of Sciences. Perhaps one of the most perplexing aspects of this time period was the failure of the EPA and NRC to reach an agreement on a radiation protection standard, 15 millirem a year *versus* 25 millirem a year, respectively (GAO, 2000). In 2001, DOE amended its original guidelines in 10 CFR 963 and focused on the evaluation of criteria for the suitability of the Yucca Mountain site.

During this long history, the most important document is the National Research Council's report of 1995, *Technical Bases for Yucca Mountain Standards*. Importantly, this committee recommended a risk-based standard,

rather than a release-rate standard, argued that the compliance assessment should extend through the period of maximum risk (*e.g.*, peak dose) and expressed confidence that the physical and geologic processes could be sufficiently quantified and the uncertainties bounded well enough that the performance of the repository could be assessed for a period extending to one million years. Previously, the EPA standard and NRC implementing regulations had extended to only 10,000 years. Despite clear statements supporting a compliance period extending through the period of peak risk and confidence in the ability to make such an analysis, the committee did recognize that there were policy aspects of this recommendation that had not been addressed (2nd paragraph of page 56), such as establishing a consistent policy for managing the risk from radioactive and hazardous materials.

Despite the recommendations of the 1995 Academy report, in 2001, EPA promulgated a standard that retained the 10,000 year compliance period. The same year the NRC promulgated its final site-specific regulation, 10 CFR Part 63, for Yucca Mountain with a compliance period of 10,000 years and a dose limit of 15 mrem; however, the generic regulation, Part 60 remained as written. Of the many lawsuits brought by the State of Nevada against the federal government, only one prevailed. In July, 2004, the U.S. Court of Appeals remanded the EPA standard, because EPA had failed to follow the instructions of Congress in the 1992 Energy Policy Act and develop a standard based on the recommendations of the NAS. In 2008, the final EPA standard was revised and issued with a dose limit of 15 millirem for the first 10,000 years and a dose limit of 100 millirem from 10,000 to one million years. It also required that DOE consider the effects of climate change, volcanic activity and earthquakes over this 1 million year period.

1.2 Key Points in the Evolution of the Standard and Regulations

This short history of the efforts of the EPA, NRC and DOE to develop criteria, standards and regulations for the selection and evaluation of a geologic repository does not present every step in the process or the nuances of the different approaches to determining compliance with a regulation. That story is much too long for this short paper. However, one can identify trends in the evolution of the regulatory approach.

- The initial efforts by all three agencies were mainly to establish generic criteria, standards and regulations. After the Congressional decision to focus all effort on Yucca Mountain, the regulatory framework changed, and all three government agencies focused on a site-specific standard and regulations.

- The initial generic criteria, NRC 10 CFR Part 60, focused on the properties of the materials or geologic system with maximum waste

package release rates and minimum ground water travel times. These subsystem requirements reflected the multiple barrier or "defense-in-depth" philosophy that was meant to provide redundancy and confidence in the disposal strategy. As the thinking evolved, and particularly with the Academy report in 1995, the subsequent emphasis was on developing a risk-based or dose-based standard. The evaluation of dose required a total system analysis from the release of radionuclides from the waste form to exposure to an individual at some distant place and time. Since total system performance was the measure of compliance, subsystem requirements were no longer viewed as necessary or desirable.

- The initial compliance period was 10,000 years, based on the fact that the level of radioactivity and thermal output would decrease substantially during this period. Also, there was concern that "predictions" beyond this period would have little basis and be difficult to justify. Based on the recommendations of the NAS report in 1995, the final EPA standard extended the compliance period to one million years in order to include the time at which a peak dose might be realized.

- Beginning in the mid-1970s, there was a steady movement toward the use of performance assessment, a probabilistic risk analysis first developed for nuclear reactors, for the evaluation of a geologic repository (Ewing *et al.*, 1999). This shift toward PA was based on the belief that there had been "considerable evolution in the capability of technical methods for assessing the performance of a geologic repository." Much of the initial analysis was applied to the evaluation of the Waste Isolation Pilot Plant for transuranic wastes. In the final rule-making for Yucca Mountain (10 CFR Part 63), the critical criterion for determining compliance was to be the numerical results of PA modeling. Still, the EPA (40 CFR Part 191) had acknowledged that the "proof" of future performance could not be obtained in the same sense as one might expect for shorter time frames.

- From the earliest point, one of the key issues has been the uncertainty in the evaluation of the performance of a geologic repository on a scale of tens of kilometers over periods of hundreds of thousands of years in a complex and heterogeneous geologic system. Early thinking relied on qualitative confidence in a series of multiple barriers, with each barrier serving an independent function over varying time scales. Engineered barriers, such as the waste package, would be most effective immediately after the wastes were emplaced and when the wastes were the most dangerous. Geologic barriers, such the slow movement of ground water, the high sorptive capacity of the geologic formations and dilution during transport, would provide barriers over longer periods.

The most recent approach requires quantitative assessments of total repository performance and the associated uncertainty in that determination.

As a result of the evolution of the regulatory approach, the licensee now is required to demonstrate compliance by completing a total system performance assessment that consists of many dozens of models of a wide variety of processes, which in the case of WIPP, as an example, required over one thousand input parameters. These models are coupled to one another in a complex way and then used to describe the behavior of the geologic repository over very long periods. ***The essential question is whether such an analysis, by itself, should be used to determine whether a geological repository is safe?***

Finally, the evolution of the regulations has led to the awkwardness of having essentially two sets of regulations, the generic regulations 10 CFR Part 60 *vs.* the site-specific 10 CFR Part 63. A site, such as Yucca Mountain, may pass the site-specific criteria, but fail the generic criteria (Murphy, 2006). As examples:

- The gaseous ^{14}C release from fuel emplaced in the unsaturated zone could exceed the release limits for the engineered barrier system in 10 CFR Part 60.

- The fundamental instability of UO_2, the main component of spent nuclear fuel, in an oxidizing environment may exceed the release rate limits of 10 CFR Part 60.

- The ground water travel times at Yucca Mountain may exceed the 10 CFR Part 60 limits, as evidenced by the presence of bomb-pulse ^{36}Cl at the repository horizon some 300 meters below the surface.

- Rapid transport of radionuclides could lead to noncompliance at the 5 km boundary stipulated in 10 CFR Part 60, as compared with the compliance boundary at 18 km for 10 CFR Part 63.

While one can follow and understand the rationale for the evolution of the standard and the regulatory structure, this evolving situation did not build public, or even scientific, confidence in the regulatory framework.

2. Critical Issues

As the standard and regulations evolved, a number of issues surfaced as being of particular importance. In light of the discussion of these issues, I make some brief comments and recommendations.

2.1 Criteria for a Geologic Repository vs. Compliance with a Standard.

The early efforts of site selection required some sense of what would constitute a suitable or unsuitable site. In 1978, the National Research Council issued its report, *Geological Criteria for Repositories for High-Level Radioactive Wastes*. This short report provides a common-sense list of the attributes that might exclude an area from consideration as a geologic repository. In that same year, Bredehoeft *et al.* published *Geologic Disposal of High-Level Radioactive Waste – Earth-Science Perspectives* as USGS Circular 779. This was a prescient description of the challenges of geologic disposal. These authors offered a clear outline of the physical and chemical changes that would be critical to the evaluation of repository formations with emplaced waste, the difficulties of site characterization, the relevant properties of groundwater systems, and the time frames over which geologic predictions might be made. Most importantly, they linked predictions of repository behavior to the evaluation of risk. Given this solid foundation, why have we failed to develop a repository for spent fuel and HLW after 30 years?

I think that in part this is due to a *failure to use the initial site-selection criteria as a critical part of the site selection process.* The value of the criteria is not that they necessarily ensure that a repository will finally comply with a standard, but rather, if followed, they can reduce the complexity of the safety assessment and the determination of compliance. As an example, the NRC (1978) criterion (3.2) emphasized the need to select areas that exhibited long-term geologic stability, such as the absence of tectonic boundaries or evidence for relatively recent volcanic activity. At Yucca Mountain tremendous effort was absorbed in dealing with seismic (Applegate, 2006) and volcanic (Crowe *et al*., 2006) activity. Selecting a site in an active tectonic region, such as the Basin and Range province of the western U.S., added a substantial burden to the safety analysis and the determination of uncertainty in that analysis. The rocks of the repository horizon at Yucca Mountain are only some 13 million years old. If the standard stretches to one million years, proof of long-term stability would be more easily gained in geologic terrains that are on the order of hundreds of millions of years of age. The NRC (1978) criterion (4.) also recommended that repositories not be sited in areas with "present or past record of resource extraction." With its oil and gas resources, the Carlsbad region fails this criterion. For this reason, in the case of WIPP, the human intrusion scenario, with its estimates of drilling rates in the region, becomes a critical aspect of the performance assessment. In fact, what matters most at WIPP is the prescribed

drilling rate (100-year average), as described by Peter Swift to the BRC on July 7, 2010. I view it as unfortunate that the judgment of the safety of a site essentially rests on assumptions about the future rather than on the geologic properties of the site itself.

In summary, a site selection process is well guided by common sense criteria that must be used as a first step in the process. If during site characterization it is discovered that the site does not meet the technical criteria, then it should be abandoned. A "suitable" site is not only one that matches the criteria, but also one for which the analysis of performance over long periods is tractable and believable. No site will be "perfect", and there will always be trade-offs in the final judgment. But an important criterion should be that the site itself be an effective barrier to the release of radionuclides – and this judgment should not depend on assumptions in the analysis. ***The determination of compliance with a standard is the last step in the process after extensive site characterization, but the success of this last step depends critically on the wisdom that supports the first step in the site selection process.***

2.2 Features of the Standard & Determination of Compliance

In September of 2008, the EPA finally issued a site-specific standard for Yucca Mountain. This final standard was in response to a previous standard being remanded in federal court in 2004. The NRC regulations (10 CFR Part 63) issued in 2001 remained in force. The principal features of the final standard included:

- dose limit of 15 millirem per year for the first 10,000 years after disposal;
- dose limit of 100 millirem annual exposure per year between 10,000 and 1 million years;
- point of compliance at 18 km distance from the repository;
- exposure determined to the reasonably maximally exposed individual.

With the extended period of compliance, to one million years, EPA required consideration of much longer-term processes, such as climate change, volcanic activity and seismic events.

The Yucca Mountain standard and regulations evolved over more than a quarter of a century. In the absence of Yucca Mountain as a repository, the process must be repeated. Reflecting on the difficulty and controversy of developing the standard and regulations, I make the following observations and recommendations:

- ***A single agency should be responsible for developing the standard, supporting regulations and determining compliance.*** Much of the delay and confusion (*e.g.,* the 15 millirem *vs.* 25 millirem standard controversy) were due to the inability of the Nuclear Regulatory Commission and the EPA to arrive at a single position. As discussed below, developing regulations for compliance is an integral part of setting the standard. Considering the different possibilities for how compliance might be determined and the need for consistency, it is best that a single agency bear both responsibilities. I suggest giving careful consideration to the fact that the EPA has extensive experience in regulating a wide range of contaminants (hazardous and toxic chemicals) in the geosphere and biosphere. This experience will certainly be of great value in regulating radioactive materials in a geologic repository. I also note that the EPA is the regulator of the only successful repository in the United States, while the Nuclear Regulatory Commission has been recently politicized, and its credibility substantially diminished.

- ***Prior to the site selection process, the responsible agency should be required to develop a final, generic standard and supporting regulatory framework.*** A generic standard can then be applied to a variety of sites. This should be possible, as over a quarter of century of effort and thought have already gone into this process. Having a generic standard will support the efficient examination of multiple sites. Scientists and engineers who develop the waste disposal strategy, select the site, and design the repository need to have a clear statement of the regulatory requirements. In the case of Yucca Mountain, the development of a site-specific standard at the same time that the site was under investigation lead to the clear, and perhaps fair, impression that the standard was "adjusted" to "compensate" for the less favorable qualities of the site.

- ***A generic standard adds much to the credibility of the process.*** As an example, a site-specific point of compliance is too easily adjusted to the properties of the site. Extending the point of compliance has the effect of compensating for release from the near-field of the geologic repository. Specifically, in the case of Yucca Mountain, the performance assessment relies in a major way on the sorption, dispersion and dilution of radionuclides in the deposits along the 18 km path to the point of compliance near Lathrop Wells. The concept of geological disposal was never intended to include such a distant geologic barrier. In contrast, the WIPP site boundary is a square, four miles on an edge, which extends vertically to the repository horizon. For WIPP, there are two general, but essentially different, types of quantitative requirements. The first is a general containment requirement that limits the cumulative quantity of

radioactive material that may migrate beyond the boundary to the accessible environment over the compliance period of 10,000 years. During this period, DOE is also required to consider human intrusion scenarios, such as deep drilling. The second requirement consists of individual and ground water protection requirements that apply to doses received by an individual over a human lifespan *via* ground water transport to the accessible environment, even if outside of the control area of 16 square miles.

- ***The dose limit should be generic, applicable to all sites.*** The 15 millirem dose limit during the first 10,000 years for Yucca Mountain is consistent with the dose limit for WIPP during 10,000 years. The unusual aspect of the Yucca Mountain standard is the increase to 100 millirems beyond 10,000 years. The increase in the dose after 10,000 years reflects an effort to cope with the uncertainty in the analysis over such extended periods. I simply note that it is an unusual strategy to accept a higher dose in the face of uncertainty.

In summary, the spatial, temporal and dose requirements of the standard should be equally applicable to any site that is selected for the design and development of a geologic repository. ***The standard and supporting regulations must exist before the site is selected. An evolving standard, tied to a specific site, will inevitably be suspect. For geologic disposal the selection of the site is the most critical step in the process; thus, considerable thought should be devoted to site-selection criteria.***

2.3 Compliance Period: What happens at 10,000 years?

As described above, the initial standard was for 10,000 years. The initial thinking that supported 10,000 year standard was that most of the risk would have disappeared by this time due to radioactive decay. Additionally, this was the longest period of time that one could reasonably expect to model and evaluate the performance of the repository, and this was also a period over which one did not expect major geologic changes that could impact the safety analysis. However, based on the recommendation of the National Research Council (1995) and as subsequently required by Federal Court in 2006, the EPA extended this standard to 1,000,000 years in 2008. ***This single change, particularly coming so late in the development of the license application that was submitted in 2008, more than any other factor, has confounded the effort and credibility of the evaluation of the safety of Yucca Mountain.***

Because the recommendations of the National Research Council (1995) had such a profound effect (as was required by Congress) on the final EPA regulation, it is important to review the basis for their recommendation for a compliance period that extends well beyond 10,000 years.

The committee discussed two technically based reasons for the 10,000 year period and rejected both. The first is that uncertainties in the analysis would become too large for periods extending beyond 10,000 years. The NRC committee judged that "assessment is feasible" and that the ultimate restriction on time scale is determined by the long-term stability of the "fundamental geologic regime," which was some one million years for Yucca Mountain. There is no discussion of what is meant by the "stability" of the "geologic regime" or the scale of the region to be considered in defining the "geologic regime." As an example, would the "stability" include the recent volcanic activity to the south of the site that is less than 100,000 years old? Or when considering WIPP, which is located in salt layers that are more than 200 millions old, should the compliance period be longer? There is no discussion of the basis for the conclusion that the "assessment is feasible" and no discussion of how the uncertainty in that assessment could be evaluated.

The second technical reason that might be the basis for a 10,000 year period is that there would be no significant health effects after a specified time. The NRC committee found that some potentially important exposures might not occur until after several hundred thousand years. The committee concluded:

> "For these reasons, we believe that there is no scientific basis for limiting the time period of the individual-risk standard to 10,000 years or any other value. We recommend . . . that compliance assessment be conducted for the time when the greatest risk occurs, within the limits imposed by the long-term predictability of both the geologic environment and the distribution of local and global populations." (NRC, 1995, p.55)

It was on the basis of this reasoning that the EPA yielded in their revised standard and created a 1,000,000 year standard.

I will not critique the NRC (1995) report in detail, but I think that it is worthwhile pointing out some of the contradictions in the few pages of this report that discuss the compliance period:

- A risk-based standard requires the calculation not only of the geologic performance of the repository but a calculation of the exposure to human beings. This depends critically on the future distribution and habits of the populations that occupy the repository area. Considering that the human species spread across the world in a period of some 50,000 years, predictions of the distribution of human beings and their habits in a million years is a fantasy. The committee made exactly this point earlier in their discussion when they noted, ". . . there is no scientific basis for prediction of future states, and the limit of our ability to extrapolate with reasonable confidence is measured in decades or, at most, a few hundred years."

- In a later (Chapter 3), but short, discussion of the time scale, the committee notes that "In comparison with many other fields of science, earth scientists are accustomed to dealing with physical phenomena over long time scales. In this perspective even the longest times considered for repository performance models are not excessive" (page 71). This is certainly true, earth scientists routinely deal with processes that extend to the earliest history of Earth, some 4.5 billion years ago, but the models and understanding of these very long time Earth processes are not accomplished by using methods that are similar in any way to the proposed assessment methodology – probabilistic performance assessment. The report is sadly silent on how to deal with geologic systems over relevant time periods. Furthermore, it is not only the physical processes that are important. One must also consider geochemical processes.

- Finally, the rationale for extending the compliance period to the time of highest risk, that is the peak dose, has some awkward implications. At Yucca Mountain, this reasoning extends the compliance period to many hundreds of thousands of years. However, imagine two types of repositories. The first is very poorly designed, and there is a rapid and high release of radionuclides to the biosphere resulting in an early peak in human exposure. This very early peak of exposure would be followed by lowered exposures as radionuclides decay and are dispersed in the geosphere. The second repository has an excellent design and release of radionuclides is delayed for hundreds of thousands of years. The peak dose would be extremely low, but that peak might not occur for a million years. Does it make sense to have the shortest compliance period for the worst repository?

I am not arguing for a shorter or longer compliance period, but I do suggest that there are other ways to construct a standard that assures the short term safety of known, or reasonably known, future populations and still uses to advantage the potential for long periods of geologic isolation.

2.4 Determination of Compliance –What is the Standard-of-Proof?

Establishing a standard and supporting regulations is only the first step required to successfully license a geologic repository. The second, and more demanding, step is to demonstrate compliance. As described by the NRC (10 CFR 63 subpart E) the principal requirement is reasonable assurance that the there is a demonstration of numerical compliance with the standard based on a performance assessment. At the time, 2001, that 10 CFR Part 63 was promulgated, the compliance period was 10,000 years. Even for this relatively short period (as compared with the present standard of 1 million years), there

was considerable concern about the usefulness of a probabilistic performance assessment in determining the safety of a geologic repository, particularly considering the large uncertainties inherent in such an analysis (Ewing *et al.*, 1999).

A typical performance assessment of a geologic repository requires a coupling of models of atomic-scale processes to continental-scale processes, such as earthquakes and volcanism, and finally, to global-scale consideration of climate change effects. The performance assessment of Yucca Mountain includes models of molecular-scale corrosion of spent nuclear fuel, nuclear waste glass and metal canisters, complex chemical interactions of fluids, waste forms and rock in the near-field, transport (dilution, dispersion and sorption) of radionuclides through the far-field, probabilistic analyses of seismic and volcanic events, and finally variations in precipitation and infiltration that result from climate change, to name just a few of processes that are modeled. Each sub-model may be extremely sensitive to assumed boundary conditions, is coupled to other sub-models, and the behavior of the total system is extrapolated over very long periods. Output of one model becomes either an input (*e.g*., radionuclide concentrations in solution) or a boundary condition for other models (*e.g*., percolation rate and the thermal field). Each sub-model (*e.g.,* spent fuel corrosion, climate change, fluid flow, thermal-hydrologic-chemical-mechanical interactions, dose-to-person calculations) represents a major effort and challenge within its own sub-discipline. Error and uncertainty creep into every step of the analysis. The sources of error include:

- The wrong conceptual model of the physical and chemical processes may be used.
- The inevitable simplification or abstraction of the models may not capture the behavior of specific parts of the repository.
- The conditions of the repository evolve over time; hence, important boundary conditions change (*e.g.,* infiltration rate).
- Input parameters or parameter distributions may be in error.
- Analytical solutions may be wrong.
- The description of the geologic system may be incomplete.
- Incorrect probabilities may be assigned to events (seismic or volcanic)
- The coupling of different models may lead to unexpected, nonlinear behavior.

All of these sources of error are confounded by the need to complete an analysis of the *total system performance*. The analysis of the total system requires a simplification of the component models. But the premature simplification of complexity may well hinder the ability to understand the system.

Much has been written on the application and utility of the PA approach in evaluating the performance of a geologic repository (*e.g.,* Ewing *et al*., 1999). In

addition to the scientific limitations of doing such an analysis, there are other limitations:

- The analysis is opaque and is, in fact, difficult to review. It is certainly not accessible to the broader scientific community who may have a specific expertise in different aspects of the analysis.

- The results often depend more on the assumptions than the actual properties of the site. Optimistic assumptions about one part of the system, such as canister lifetime, can reduce the apparent importance of other parts of the system, such as waste form durability.

- The uncertainty is difficult to quantify (*e.g.,* parametric, conceptual, changing boundary conditions and scaling effects).

- It is very difficult to convey the results of such an analysis to the public.

Based on my experience reviewing the performance assessments at WIPP and Yucca Mountain, I conclude:

- ***Performance assessments are not quantitative***, but rather provide a qualitative result. The uncertainties in the results remain large and increase with time. Generally, the PA does not adequately address the issue of conceptual model uncertainty, the impact of changing boundary conditions or scaling effects.

- Treating the results as "quantitative" causes regulatory agencies to concentrate on the numbers rather than the strategy for the safe disposal of nuclear waste.

- PA is a necessary part of the political and regulatory process, but it may be of limited value in supporting strategies for safe disposal of nuclear waste.

- PA is not, by itself, a sufficient basis for determining that a site is safe for the disposal of SNF or HLW (Ewing, 2006). *In fact, PA can become an Achilles Heel of such an effort, as controversy focuses on details of the analysis rather than the overall case for safety.*

3. Possible Structure of a Standard

The fundamental difficulty with previous approaches in establishing a standard has been that they have confounded human time-scales with geologic time-scales. The differences between these two scales are not simply a matter of the length of time, but rather is a difference in how one analyzes the

performance of the repository and demonstrates compliance. The difference in the time scales is often lost as repositories are discussed. As an example, WIPP is a success on the human time-scale because disposal rooms have been excavated, wastes have been transported to the site and emplaced, and there have been no radiation exposures during the operation of WIPP. However, WIPP cannot yet be judged as a successful repository because this is only demonstrated over a longer geologic time-scale. The confusion of operational safety with repository performance is just one example.

There is also the issue of uncertainty and how it evolves over time. The analysis of safety will always have uncertainty, and distant futures are less well known than tomorrow. Tomorrow's weather is generally predictable because of the combination of good physical models and experience. The day-to-day predictions become more difficult over longer times. Importantly, global trends over very extended periods can be predicted, although these predictions, such as global warming, can be initially controversial and finally require a preponderance of evidence from many different sources.

Because the uncertainty in the analysis grows with time, the idea that it is useful to calculate a dose to a person exposed to radioactivity some 18 kilometers from Yucca Mountains in 1,000,000 years in order to determine whether the repository is safe diminishes the credibility of all who participate in such an effort. Just as predicting the climate in the year 1,000,2050 would be viewed as very difficult and probably not very useful, and no amount of statistical analysis can dress-up such efforts. Our understanding of the science should guide the regulatory approach. Scientists and engineers should not be asked to complete an analysis that is portrayed as being "quantitative" in order to satisfy numerical regulatory requirements, but at the same time is barely believable.

A reasonable standard should recognize the two time-scales and be designed accordingly, recognizing limitations in understanding and prediction, but without compromising the confirmation of safety. As an example, the standard-of-proof is different for human time-scales, as compared with geologic time-scales. The type of "proof" required to understand geologic systems over very long periods is very different from that required to demonstrate the reliability of engineered systems. As very eloquently discussed by Oreskes (2004):

> " . . . it seems clear that science does not require proof – neither in the sense of a direct detection or measurement, nor in the sense of certainty or unanimity – to advance. Science can and does proceed on the basis of indirect evidence and abductive inference, so long as the evidence and the inferences are acceptable to relevant scientific experts."

On a human time-scale, perhaps as short as a few thousand years, certainly not extending beyond recorded human history, one can expect quantitative estimates of release and radiation exposure to have some usefulness. Over longer periods one may do calculations, but the calculations themselves cannot be the basis for the determination of safety, as the uncertainties are too large. For the longer periods there must be a compelling case based on the positive attributes of the site as determined during site selection and characterization. One also has to realize that the two time scales do not apply to all parts of the repository in the same way or over the same periods.

As an example, for the shorter human-scale period, one expects the standard to depend on a fundamental understanding of the reliability of engineered barriers – waste form, backfill, canister materials, near-field interactions. Models of waste form degradation, swelling of backfill in contact with water, corrosion of metallic canisters, and the solid-water interactions in the near-field should reflect the present state-of-science without unnecessary simplification. The point of compliance can be at a short distance, perhaps some kilometers, close to the disposed, radioactive material. A durable waste form, thick metallic canisters, a functional back-fill, geochemical conditions that reduce radionuclide solubilities, and the hydrological properties of site would all contribute, as individual barriers, to minimal release levels. Barriers should, as much as possible, operate and be evaluated independently. Uncertainty would be addressed by a series of multiple barriers, each with a substantial capacity for controlling the release of radionuclides. As an example, if the compliance period is 2,000 years and the canister lifetime is 5,000 years, the canisters would be the principal barrier, but in a true multi-barrier system, one would also require that in the absence of a canister, the release would still meet the regulatory requirement. The emphasis on this near-field containment over a human time-scale would be on protecting present populations and their more immediate progeny. Thus, dose- or risk-based calculations would be appropriate, but also be supported by compelling evidence of an effective and reliable series of multiple barriers.

For the geologic time-scale analysis, a "quantitative" analysis may provide insight into how the geologic system works and how the different geologic barriers (*e.g.*, sorption onto mineral surfaces and ground water flow rates) interact, but **the success of the geologic containment system can only be judged by formulating a safety case, that is a compelling argument as to the fate of the radionuclides in the repository environment over time.** The use of a safety case for the long periods of geologic containment, as distinct from a safety assessment, is a commonly used approach in other national programs and is well described in a recent NEA (2009) publication that summarizes the different approaches taken by different countries. For the geologic time-scale, the geology would be the primary barrier. As such, geologic time-scales are appropriate. One may also have a different point of compliance, more distant from the repository, *e.g.,* 10 kilometers, which would take

advantage the geologic properties of the surrounding rock. It is important to realize that over longer periods, the problem becomes simpler. At longer times, many of the problematic radionuclides will have decayed away, and only a short list of radionuclides requires attention, such as: ^{135}Cs, ^{129}I, ^{99}Tc, and actinide elements, such as U and Pu. The safety case would examine each of the problematic radionuclides and determine their fate in the expected geologic environment. The argument for safety would vary from element to element. One might argue that ^{129}I would be isotopically diluted by non-radioactive iodine in the environment, while the actinides would be examined in terms of their mobility under the expected range of geochemical conditions. A wide array of different sources of evidence might be cited, such as the fate of actinides in the Oklo natural reactors over the last two billion years. The safety case would take the form of the type science that is characteristic of the earth sciences: inference based on other similar types of rock, careful observation of natural systems, and models that are well-grounded in fundamental physics and chemistry. For the geologic time-scale safety case, there would be no need to evaluate dose levels, except as illustrative examples – *but not for the purpose of determining compliance.*

Such an approach would be a radical departure from present practice and highly controversial. In contrast to present practice, this science-based analysis would focus on subsystem performance and reduce reliance on a total system evaluation of dose or risk. This does not mean that large parts of the system would not be evaluated as a unit, but it does mean that the analysis would focus on what is known and the quality of the science, and not on the statistically modeled behavior. With the present regulatory approach the focus is too much on the properties of the model and not the anticipated behavior of the actual repository (Ewing, 2006).

Such a science-based approach would require detailed analysis by relevant experts, inevitably result in moments of controversy among experts, and require additional investigations as the effort moves forward. In other words, it would be entirely consistent with how science actually works. This is how the earth sciences deal with complex questions, such as climate change or plate tectonics, which encompass large tracts of Earth's crust over very long periods of time. The final determination of compliance by a regulatory agency would require an institution of considerable expertise and integrity.

4. Relation of Science to the Standard – "When do I know enough?"

One of the difficulties of having a quantitative standard has been that the regulator and the licensee both work toward that "magic number". Worse than working toward the "number" is the contractors' desire to know when they know enough, basically a desire to short-circuit the expense and time required for additional scientific investigations. As an example, if the analysis demonstrates compliance due to waste package longevity or because the

presumed drilling rate is expected to be low, then the project management presumes that they "know enough," and that there is no need for further scientific investigation. This was certainly the case at Yucca Mountain where reliance on the lifetime of the fuel cladding and metal waste packages seemed to work well enough with a 10,000 year standard; hence, the geochemical properties of spent fuel were not very well investigated until after the standard had been extended to 1,000,000 years.

The regulatory framework should be designed to stimulate the application of increased understanding and scientific inquiry, because the safe management of radioactive waste is not a project with an end-date, but rather a continuing effort and responsibility of humankind.

Annex

Classification of Radioactive Wastes

The classification of radioactive wastes is the first step in determining the type of disposal. In the United States, the classification is based on a determination of the source of the waste, not their radiological properties. Radioactive waste generated by the nuclear fuel cycle fall into five categories (see NCRP Report 139, 2002), each with a designated disposal strategy:

Type of Radioactive Waste	Designated Disposal Strategy
spent fuel	geologic repository
high-level waste	geologic repository
transuranic waste	geologic repository
low-level waste	near surface/geologic repository*
mill tailings	near-surface

*high-activity, longer-lived waste may be judged to require disposal in a geologic repository (after NCRP Rept. 130)

The value of such a classification is that it prevents the dilution of the waste to lower levels of radioactivity becoming a justification for less expensive disposal strategies, *e.g.*, deep geologic disposal *vs.* near-surface disposal. The disadvantage is that such a classification fails to account for the actual radiological and chemical characteristics of the waste, which is often a complex mixture of radionuclides of very different properties. This has led to a long list of difficulties and ambiguities in determining the proper disposal environment for different types of waste (see NRCP Report 139, pages 15-16).

There is a strong consensus that a risk-based classification of the waste would provide the greatest protection to the public and avoid unnecessary expense and effort in handling radioactive wastes (ICRP Report 139, 2002). A risk-based classification is consistent with the recommendations for a risk-based standard (NRC, 1995), and it is a recommendation of the recent MIT study (2010). The value of a risk-based classification is that it should offer clear indication of the type of disposal that is required – such as deep geological *vs.* near-surface disposal.

Although the approach has much to commend it, *the critical issue is how one calculates the risk.* The full calculation of risk will require generic assumptions about the geologic disposal environment, the spatial point at which risk are calculated, the time period and the exposed population. Most concepts place a radionuclide into a disposal system and calculate the risk as a sum of the radiological properties of the radionuclide, its mobility in the disposal environment and finally the exposure to a human being. Such stylized calculations can be prescribed and used as a basis of comparison, but they will

become controversial if they are purported to represent actual risk. These calculations will depend critically on assumptions about the geochemical environment, the hydrologic conditions, the location and distribution of human populations, *etc.* As pointed out by Lowenthal (1998), "Risks cannot be properly assessed without consideration of the context of the risk including, to vary degrees, the setting in which the exposure occurs and the actions of the receptors (the individuals at risk)." The NCRP (2002) has proposed a generic risk-assessment based on the presumed qualities of a site and an evaluation of the human intrusion scenario.

A potential pitfall of such an approach is that optimistic assumptions about the geologic "context" of disposal could lead to a judgment of low risk and subsequent disposal in a different, and perhaps, high-risk disposal environment. Complications may also arise as one considers different compliance periods, that is the human-scale *vs.* the geologic-scale for time. As an example, the calculated risk from short-lived fission products, such as ^{90}Sr and ^{137}Cs, may be judged to be very low over time periods of hundreds of thousands of years, as 99.9% of the activity will have decayed away in less than 1,000 years. However, on a human-scale period, the near-surface storage of these sources of highly ionizing and penetrating radiation may be of high risk in a near surface storage environment. In fact, most contaminant problems, such as toxic metals, are of most interest to the pubic over very short periods, just a few decades. ***The calculation of risk could become a major point of contention in developing a risk-based classification and the determination of different strategies for disposal.***

A more qualitative approach would be to focus on the radiological and chemical properties of the radionuclides (see Hedin, 1997, as an example), independent of any imagined disposal environment. Based on half-life, type of radiation emitted, radiotoxicity, and geochemical mobility in the geosphere, a quality factor, Q, might be assigned to a particular radionuclide. Long-lived, alpha-emitters, such as ^{237}Np, might be given a value of 10, and require disposal in a geologic repository, while short-lived radionuclides that are less mobile in disposal environments, such as ^{137}Cs, might have a value of 1 and qualify for near-surface disposal. This is analogous to the present procedure used to calculate an effective dose from radiation. Such an approach would provide a qualitative assessment of risk, without the need to make any assumption about the disposal environment or the scenario for release.

The classification of waste will become an even more important issue as the nation considers advanced fuel cycle with different levels of reprocessing. The capability of removing high-risk radionuclides from the waste stream and developing durable waste forms (NRC, 2011) that are placed into compatible geologic environments that insure long-term durability mean that the classification should provide enough flexibility so that such strategies can be realized.

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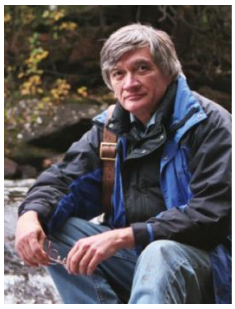

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