WHAT HAVE WE LEARNED ABOUT GEOLOGIC DISPOSAL FROM THE YUCCA MOUNTAIN PROJECT EXPERIENCE?

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I am very pleased to be here. So far, this has been an outstanding conference honoring an outstanding person. In my remarks today, I want to do two things. First, I will present my perspective on lessons learned about high-level radioactive waste disposal from the U.S. Nuclear Waste Technical Review Board's evaluation of the U.S. Department of Energy's (DOE) investigation of the proposed Yucca Mountain repository site. Second, I will offer some of my personal views on ongoing nuclear waste issues and possible paths forward.

THE NUCLEAR WASTE TECHNICAL REVIEW BOARD

The Board was established by Congress in the Nuclear Waste Policy Amendments Act (NWPAA) of 1987. The Board is a technical and scientific peer review body and an independent federal agency. The eleven Board members are appointed by the President from a slate of candidates nominated by the National Academy of Sciences (NAS). The Board's congressional mandate is to evaluate the technical and scientific validity of DOE's activities related to implementing the Nuclear Waste Policy Act and to report its findings and recommendations at least twice each year to Congress and the Secretary of Energy. The Board was granted access to draft DOE documents so that it could make its recommendations before final waste-disposal decisions are made.

In particular, the Board conducts technical evaluations of DOE's progress in understanding how the engineered and natural systems of the repository would work together to isolate radionuclides and how realistic DOE's performance estimates are. In conducting its evaluation, the Board is not constrained by judging the *adequacy* of compliance arguments or predictions—we leave that to the U.S. Nuclear Regulatory Commission (NRC). The driver for the Board's evaluation is a realistic assessment of radiation doses at the accessible environment.

THE YUCCA MOUNTAIN SITE

After encountering numerous obstacles to the siting of a permanent geologic repository, Yucca Mountain was selected by Congress in the NWPAA as the sole site to be characterized for that purpose. Yucca Mountain is located in the northern Mojave Desert about 90 miles northwest of Las Vegas, Nevada. It is a ridge of volcanic rock that receives sparse precipitation. A repository at Yucca Mountain would be constructed above the water table in fractured unsaturated rocks. That it is an unsaturated site makes Yucca Mountain unusual among potential nuclear waste repository sites worldwide: other countries have chosen to study sites in the saturated zone—for example, in clay or granite. In other ways, Yucca Mountain shares many of the challenges associated with all geologic repository development efforts—it is a first-of-a-kind endeavor that must perform for uniquely long times. In addition, aspects of the Yucca Mountain geology are complex, so gaining a realistic understanding of the site's characteristics and assessing potential repository performance are challenging tasks.

LESSONS LEARNED

There are, of course, numerous issues associated with developing a program for managing spent nuclear fuel and high-level radioactive waste before closure of the proposed repository. However, for the purposes of this talk, I will focus primarily on issues related to postclosure performance. In that context, I believe that the overarching lesson learned from the Yucca Mountain experience is the difficulty of quantifying the containment capability of a geologically complex natural system, especially when the natural system must isolate something that is as chemically complex as radionuclides locked up in slowly deteriorating spent nuclear fuel and vitrified high-level radioactive waste. It is difficult because assessing the postclosure performance of Yucca Mountain is a search for small amounts of radiation that might reach the accessible environment at a boundary set by regulation after traveling through many kilometers of heterogeneous geological and geochemical environments—not only in the three dimensions of space but in the fourth dimension of time, as well. Performance assessment is further complicated by changes to the natural system caused by disturbing the rock zone through construction activities, perturbing the atmosphere in the drifts, introducing natural and engineered materials in the repository tunnels, and, perhaps most important of all, introducing a strong and long-lived heat source, all of which profoundly complicate the realistic representation of natural system processes by computer models.

The site-characterization program developed by DOE in the late 1980s was designed to provide the technical data needed to assess waste package corrosion, thermomechanical and thermohydrological effects, the radionuclide source term, water flow and transport in the unsaturated and saturated zones, and performance impacts of igneous and seismic events. The site-characterization program has yielded significant data. However, because of continuing uncertainty associated with predicting aspects of the potential behavior of the site, it is necessary to rely to a considerable extent on laboratory tests, expert judgment, and modeling assumptions.

Heat Effects

Waste package corrosion **–** Radioactive decay of nuclear waste inside repository waste packages is a strong and long-lived source of heat. According to current plans, during the preclosure period, most of the waste heat would be removed by ventilation. After repository closure, waste package surface temperatures would quickly increase to as high as 210° C and would not fall below 100° C for about 1,000 years. Surface temperatures on a particular waste package would depend primarily on the amount and characteristics of the waste inside the waste package itself and the amount and characteristics of waste in waste packages next to it in the emplacement drift. During this "thermal pulse," it has been well established that certain mixtures of salts deposited on the waste package surfaces during the ventilation period can deliquesce to form thin spots of liquid on the surfaces of the waste packages, potentially resulting in localized corrosion.

The Board has continuing concerns about localized corrosion due to deliquescence at these elevated temperatures. In particular, the Board has stated publicly that "demonstrating an adequate technical basis for screening out deliquescence-based localized corrosion during the thermal pulse requires (1) determining the nitrate-to-chloride ratios that are inhibitive for the entire range of temperatures in which deliquescent brines may occur on waste packages surfaces and (2) confirming the hypothesis that the preferential migration of nitrate ions into the crevice is sufficient to maintain nitrate-to-chloride ratios that are inhibitive."

According to DOE's recent supplemental environmental impact statement, if generalized corrosion is the only corrosion mechanism, only about 10 percent of the packages will have been penetrated within one million years after repository closure and the penetrated packages would have only a few holes in them, on average. Excellent multi-year data exist on which to base predictions for generalized corrosion at low temperatures (i.e., at or below 100° C). DOE believes that it has addressed all technical issues that could arise regarding corrosion at high temperatures. However, DOE has little data on corrosion at temperatures above 100 °C and even less corrosion data at temperatures above 150° C. Furthermore, most of the data are short term, and some are equivocal. Questions persist about whether all possible aqueous environments that could exist above 100° C have been identified, whether organics in high-temperature aqueous solutions could react with components in the solutions, and, if so, whether metastable solutions would evolve.

Thermohydrological effects – Because waste package failure is the primary mechanism that will trigger releases of radionuclides and water is such an important element in waste package corrosion and radionuclide mobilization and transport, it is important to have a fundamental understanding of thermohydrological effects and the disposition of water and water vapor in the thermally-perturbed hydrogeologic environment. The timing and magnitude of the peak dose at the accessible boundary may be significantly affected by the timing of the mobilization of the waste. One aspect of the understanding of the disposition of water and vapor in the immediate vicinity of a drift after closure is the vaporization, flow, and condensation of water resulting from the above-boiling environment. Water boiled out of the rock can transport in multiple directions—*back into the drift from the boiling front* through the dried-out rock and then to cooler parts of the drift or *away from the drift out from the boiling front* into cooler partially saturated rock. While there remains considerable uncertainty about the disposition of the repository water and vapor, it remains to be determined what the actual impact will be on the timing and magnitude of the peak dose. Meanwhile, a thermal design has been implemented by specifying in-drift thermal loading and drift spacing and by assuming a theoretical response of the natural system to the specified thermal loading configuration.

Mobilization of Radionuclides and Water Flow and Transport

The source term – Following penetration of the waste packages by corrosion, water will enter waste packages and mobilize radionuclides. We have learned from investigating Yucca Mountain how important it is to properly represent the processes leading to the mobilization of dose-contributing radionuclides. In my opinion, the chemical and physical form of radionuclides constituting the source term may be the most critical aspect of the performance of a repository. Determining the source term is a difficult technical and scientific problem that requires supporting research and development not incorporated in DOE's current model. For example, to date, the physical chemistry of dose-contributing radionuclides such as neptunium and plutonium has been studied primarily in laboratories to learn how these radionuclides behave in engineered systems designed for separation and recovery. Under those testing conditions, the physical chemistry is based on results that are achieved quickly and chemical forms that can be modeled easily.

Determining the behavior of radionuclides in nature is much more difficult than in the laboratory because of the large number of possible interactions with minerals and the formation of minerals and alteration products that incorporate these nuclides. An analogy of such a situation is where fluoride wastewater from the conversion of uranium hexafluoride to oxide was treated with lime to precipitate the fluoride as calcium fluoride. The primary objective of removing soluble fluoride was achieved, but at the same time a small amount of enriched uranium in the water also was precipitated. The precipitation of uranium occurred where uranyl replaced calcium in the calcium fluoride lattice and became "locked" in the precipitate and virtually insoluble. Thus the question: Would a more comprehensive source term model lead to a very different radionuclide source term, the basic building block to the repository performance assessment?

Water flow and transport – One area of considerable progress over the past few decades is the fundamental understanding of flow of water and transport of solutes in the unsaturated and saturated zones. The key lesson learned here is that useful models can be developed in previously uninvestigated areas, such as water flow in unsaturated zones, if the proper attention is given to them. An important advance has been the development of numerical models that allow for the simulation of complex coupled processes, including advection, dispersion, diffusion, sorption, radioactive decay, and colloid-facilitated transport, along with computers capable of simulating these processes in three and four dimensions at field scales of interest. DOE computer models can reproduce with reasonable fidelity measured ambient fluid potential, temperature, and salt distributions in the unsaturated zone.

Nonetheless, rigorous understanding and high-resolution quantitative prediction of fluid flow and solute transport in *fractured* unsaturated rocks remains a challenging aspect of Yucca Mountain hydrogeologic science. For example, while observations of bomb-pulse Cl-36 at depth within Yucca Mountain are consistent with water velocities calculated by computer models, there are inconsistencies between multiple field measurements. This, in my view, simply indicates the limitations of the state of the hydrogeologic sciences regarding fluid flow and solute transport in fractured unsaturated rocks.

Matrix diffusion is another important phenomenon that could significantly slow the transport of some radionuclides from the repository to the accessible environment. Conceptual and numerical models of matrix diffusion for the fractured rocks in the unsaturated and saturated zones at Yucca Mountain have improved over time. They may continue to improve as these processes become more fundamentally understood. The Board has commented on all of these issues in communications with DOE and Congress.

High-Consequence/Low-Probability Events

Igneous and seismic issues – The long time periods involved in the performance assessment make it a certainty that earthquakes with a range of magnitudes will occur. There also is the very small chance of a high-consequence igneous event, with magma flowing into the repository or erupting onto the land surface. These are areas where it has been extremely difficult to obtain realistic assessments. Many historical assumptions in estimates of seismic and igneous consequences by DOE are conservative (e.g., in some performance assessments, it was assumed that all waste packages in the repository are affected by any igneous intrusion into the repository). The conservatisms could be reduced if more realistic models were found to be usable and defensible. DOE's program for defining physical limits to seismic ground motion could result in lower seismic doses than currently estimated. However, some conservative assumptions may be found to have little effect on the estimated dose.

Since its inception in 1989, the Board has been actively involved in seismic and igneous issues. The Board has urged DOE to make careful use of expert elicitation in determining the probability of seismic and igneous events. The Board also has recommended that DOE make known the conditional doses due to igneous events—not just the probability-weighted doses as required by the regulations. The Board has encouraged DOE to use realistic assumptions in its evaluations whenever possible. Recently, the Board focused on very high estimates of seismic ground motion being calculated at very low probabilities. At the initiative of its own science and technology program, DOE has established a program aimed at determining physical limits to ground motion. The hope is that this program will lead to more realistic results.

Compliance versus Fundamental Understanding

Introducing realism into performance calculations – One of the more interesting lessons learned from Yucca Mountain is the conflict that sometimes exists between technical assessments for fundamental understanding and technical assessments for compliance with regulations. For example, there is the problem of the calculation of actual radiation doses at the accessible boundary where the doses are very low (millirem range) and the time periods extremely long (on the order of a million years). Here the issue seems to be how to get realism into the calculation, given that so much of the calculation is prescribed by federal regulations. In particular, the U.S. Environmental Protection Agency (EPA) has proposed to place a number of constraints on the performance assessment used to predict repository performance. Although these constraints may achieve their purpose of facilitating regulatory compliance reviews, it appears to me that they also have the effect of making the calculations inherently unrealistic. For example, while no one can foresee with certainty the nature of the biosphere thousands of years in the future, we can be highly confident that it will be different from what EPA and NRC have prescribed. Another approach that might be more meaningful would be to define a reasonable range of possible future biosphere scenarios and use this range and a likelihood estimate that is based on supporting evidence to examine the possible consequences of releases from the repository.

Transparency and traceability of analyses – A major challenge for the Board in evaluating the technical validity of work performed by the Yucca Mountain Project has to do with the transparency of the supporting analyses. Of particular concern has been the traceability of repository design criteria to the thermal, chemical, nuclear, and mechanical properties of the waste form and host rock thermal hydrology. DOE has put together its performance assessment (PA) for Yucca Mountain using a bottoms-up approach: first, all features, events, and processes (FEPs) that possibly could affect repository performance are enumerated; second, those that are inoperative under Yucca Mountain conditions or that have an insignificant effect on performance are eliminated; finally, those that matter to PA are included. This process may seem obvious, but it is incredibly complicated because there are a very large number of FEPs in DOE's PA. Consequently, documentation of the technical bases for (a) including or excluding the FEPs and (b) the models for FEPs that are included in the PA, is an impediment to transparency.

Even using FEPs, assumptions must be made. DOE tries to make conservative assumptions about repository performance (i.e., predictions of risk that exceed the reality), reasoning that if the repository can be shown to be "safe" with conservative assumptions, it would be safer still if more realistic assumptions were used. But DOE's use of conservative assumptions makes realistic assessment of the potential behavior of a Yucca Mountain repository more difficult, thereby creating another impediment to transparency. In the absence of a realistic assessment, and especially because of the highly non-linear nature of the coupled physical and chemical systems at Yucca Mountain, the magnitude of performance margin afforded by DOE's "conservative" assumptions is very hard to judge. The Board has urged DOE to increase transparency by developing a simplified and more realistic performance assessment; I will have more to say on this subject in a moment.

As I mentioned earlier, other lessons to be learned at Yucca Mountain have to do with the total waste management system, including institutional or regulatory issues and waste handling and transportation activities. For example, evaluating the integration of the component parts of the waste management system and how they relate to repository criteria and site-characterization data has been a particularly challenging Board activity. In general, regulatory criteria relating to preclosure is restricted to real doses that would be received by real humans, while postclosure criteria attempt to limit hypothetical doses to hypothetical humans living hypothetical lifestyles. It appears to me that a more consistent regulatory scheme would allow a comparison of all parts of the waste management system, to identify those components or operations that pose the greatest risk and to focus design and operational expenditures on those areas where we can do the most to reduce the overall level of risk.

I also think that a direct comparison of the relative risks (safety, cost, and reduced operational complexity) associated with preclosure safety and postclosure performance would help to facilitate trade-offs among the surface facility design, the concept of operations, and the postclosure performance of the repository. However, DOE has not pursued such an approach, nor have EPA or NRC required it.

I will now depart from lessons learned from the Board's evaluation and offer some personal comments on a subject of great interest to me, and that is the problem of "decision making under uncertainty."

DECISION MAKING UNDER UNCERTAINTY

As we all know, regulators at both NRC and EPA have for several years been going through a paradigm shift, adopting a risk-informed regulatory practice. Probabilistic performance assessments are a product of that shift. Of course, uncertainty in the management of nuclear waste always has been a consideration; however, only recently have attempts been made to quantify the uncertainty. In 1957, the first NAS report on waste management proposed to address uncertainty through an elegant technical solution—bury the waste in salt. The absence of water and the self-sealing properties of salt were major contributors to the NAS recommendations. The attractiveness of the "salt" solution faded with the emergence of issues associated with heat-generating waste. The emerging position was to take a "systems" approach of engineered and natural systems to assure "defense-in-depth" in isolating the waste for many thousands of years.

NRC became aggressive in implementing a total systems perspective with risk-informed features for the management of nuclear waste, especially with respect to high-level waste. In particular, a shift was made from prescriptive requirements on subsystems such as ground-water travel time and isolation capability of various repository components to assessing radiation dose to representative individuals living 18 kilometers from the repository. Implementation issues of proposed regulations based on the new way of doing NRC business conflicted with some of the details of proposed EPA standards, such as what constituted acceptable levels of dose at the accessible boundary. Congress eventually became involved in 1992 and mandated that both EPA and NRC draft Yucca Mountain-specific standards and regulations. In particular, Congress commissioned the NAS to conduct a study, "Technical Bases for Yucca Mountain Standards," which was completed in 1995.

The resulting report, commonly known as the TYMS report, had a major impact on what took place subsequently. The resulting NRC standards and regulations represented an important step forward. Of course, the report involved a combination of what both NRC and EPA already had started, but it went further and resolved the figure-of-merit issue having to do with what the dose standard should be. The TYMS report also provided guidance on other issues, such as the human intrusion scenario. Now, the way was clear for moving forward more aggressively with a risk-informed regulatory practice, one which was desired by almost everybody. NRC's desire to make the system as a whole the basis for performance prevailed, as opposed to any requirements on subsystems. The regulatory figure-of-merit became dose to an exposed population, which can, as a function of prevailing knowledge, be transformed into a measure of risk. Finally, and most importantly from my point of view, dose/risk must be assessed using a probabilistic methodology.

The stage finally was set for officially embracing the uncertainty sciences by the regulators. Although this was a major move forward, the current situation is still murky in terms of taking full advantage of the risk sciences. This is because in a very real sense, it is clear that the proposed standards and regulations either mandate or encourage technical approaches that dilute the benefits of probabilistic risk assessment (PRA). Prescriptive requirements and multiple standards remain, depending on the duration of the compliance period, whether they apply to postclosure or preclosure, and the type of waste that is involved. As might be expected, the implementation strategy of applicants is one of a mixture of deterministic and probabilistic methods and the use of conservative assumptions that tend to mask what the experts believe is the real risk. In other words, we have a start towards the use of the risk sciences, but we have not gone far enough yet to gain the full benefit from PRA, which is a representation of the real risk in a form that quantifies and communicates the associated uncertainties.

I am not suggesting that we start anew or burden the Yucca Mountain Project for a more risk-informed performance assessment. Demonstrating whether the proposed repository system complies with the standards and regulations will be no easy task, but it is obviously one that needs to be undertaken as expeditiously as possible. Nevertheless, I strongly believe that the public should have the benefit of knowing what the experts really believe the risk is. So, here is what I would propose.

1. DOE should commit to carrying out a *de novo* performance assessment, outside the established regulatory framework, that allows project scientists to exercise their best professional judgments, unburdened by the concern of having to defend them in an adversarial adjudicatory process. They should not fall back on the use of conservatisms; they should treat low-probability events as low-probability events.

2. I would be naïve if I failed to recognize that, deservedly or not, the waste management community has been scarred by what has taken place in the past few decades. Consequently, this community is not trusted by some, perhaps many, important stakeholders. Moreover, the exercise of expert judgment required to prepare this *de novo* performance assessment is by no means "frictionless," as the NRC's Branch Technical Position on expert elicitation has forthrightly understood. So I also would propose that (a) the *de novo* performance assessment be subjected to an international peer review in which key stakeholders, including the State of Nevada, can place experts at the table, and (b) DOE commit to

developing multiple, independent lines of evidence to increase confidence in the central conclusions that emerge from the *de novo* performance assessment. Such an effort might focus on natural analogues, such as Peña Blanca, appropriate use of defense-in-depth, and the use of arguments that rely on first principles of the physical sciences.

WHAT DO I REALLY BELIEVE IS THE REAL ISSUE FOR THE YUCCA MOUNTAIN PROJECT?

I believe that the real issue at Yucca Mountain is developing public confidence in the nation's ability to adequately remove the radiation danger of nuclear waste to future generations by geologic isolation. Important to building public confidence is something the nuclear community is just not doing well at all, and that is establishing the connection of a Yucca Mountain repository to solving our energy and environmental concerns.

As just discussed, in my opinion, the performance assessments to date are lacking in several areas and there is a need to further reduce some of the uncertainties. We should not be satisfied until the evidence is indeed convincing that there is a sound scientific basis to the radiation safety case for the proposed Yucca Mountain repository. However, without prejudging the licenseability of the site, radiation dose calculations to date indicate that the margins are substantial between the uncertainties in the calculated dose levels and the levels at which biological damage to humans at the nearest accessible boundary may occur. Even if it turns out that the radiation doses currently predicted at the accessible boundary are wrong by factors of 10 to a 100, the health and safety effects are not calculated to be serious. Furthermore, unlike many threats our society faces, options exist to mitigate any unexpected consequences such as not drinking the water, not consuming the food, and even relocating people, if necessary. Such risk assurances and corrective action options do not exist on many other threats our society faces, at least based on available risk assessments. Examples of such threats are a terrorist attack in major population centers, a major hurricane in New Orleans, an abrupt climate change, an infectious pandemic disease, a large-diameter asteroid impacting the earth, major earthquakes and tsunamis on the West Coast, irreversible pollution of our ecosystem, the increasing obesity of our population, and the use of drugs and alcohol, all of which are a threat to us today, not hundreds of thousands of years in the future where the chance of any biological damage appears to be very small.

Thank you for your attention.