Yucca Mountain and High-Level Nuclear Waste Disposal

TESTIMONY OF
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HEARING ON THE STATUS OF THE YUCCA MOUNTAIN PROJECT

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MR. CHAIRMAN AND MEMBERS OF THE COMMITTEE: It is an honor to have the opportunity to address you on the issue of the status of nuclear waste disposal at the Yucca Mountain, Nevada, site.

I am a Research Associate at MIT's Program in Science, Technology, and Society. I have a PhD in geology from MIT and have been studying and publishing on the issue of nuclear waste disposal since 1996. I am editor of the forthcoming book, *Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste*. I have appended a longer biographical sketch to the end of this testimony.

Mr. Chairman, Ranking Member Jeffords, I would like to use this opportunity to discuss some of the problems with the U.S. nuclear waste disposal program and make suggestions as to how to best address these problems.

Let me begin by emphasizing that in my expert opinion, the best solution to the problem of high-level nuclear waste remains a geologic repository. On this issue all countries with nuclear energy programs are in agreement, though none has yet to open such a facility. In light of the push for more nuclear power in the U.S., even taking into consideration the President's proposed Global Nuclear Energy Partnership, it is highly likely that multiple Yucca Mountain-type repositories will be necessary. Therefore, it is imperative that we continue to work towards a solution to the problem of high-level nuclear waste.

Some policymakers have suggested that long-term above-ground storage of spent fuel is a better solution to the current problem. Their idea is to wait until a better alternative to geologic disposal is discovered. Interim storage is just that – an interim, temporary solution. Interim storage is fine for 100 years, but longer than that one cannot be assured the containers would prevent radioactivity from entering the environment. In the unlikely case that societal control is lost over the interim storage site or technological advance cannot provide a better alternative to geologic disposal in the next 100 years, interim storage fails its task and exposes future generations to radioactivity. Thus, I would argue for continued work on geologic repository disposal of high-level nuclear waste.

The main focus of my remarks will be about the Yucca Mountain site, its complex geology, the uncertainty associated with predicting future performance of a geologic repository there, and the implications for the Environmental Protection Agency (EPA) standards proposed for the site. I will conclude with some suggestions for changes to the current program.

Yucca Mountain: A Complex Geological Site

Yucca Mountain is a relatively complex site geologically. The mountain is a low topographic feature, has a low water table, and is an arid region 90 miles northwest of Las Vegas, Nevada. In the following I will provide some examples of the complexity of the site and the uncertainties in the data that arise from this complexity.

Yucca Mountain is located in the Basin and Range extensional province of the western United States, a tectonically active area. The Yucca Mountain region is both seismically and volcanically active. For example, in 1992, a magnitude 5.6 earthquake, centered at Little Skull Mountain 12 miles southeast of Yucca Mountain shook the region, including Jackass Flats, the proposed staging area for nuclear waste at which buildings sustained damage. In 2002 the same fault system produced a 4.4 magnitude earthquake.

The repository footprint itself is bounded by two faults, the Ghost Dance fault on the east and the Sundance fault on the west, neither of which appears to be active. Two other faults on Yucca Mountain are suspected of being active: the Bow Ridge fault and the Solitario Canyon fault, as are other faults in the region.[1] Earthquakes could cause rockfall on waste packages that might breach the packages. To assure that this does not happen, the Department of Energy (DOE), tasked with managing the repository, is intending to add titanium drip shields to protect waste canisters. Earthquakes can also open new fractures in the rock surrounding the repository, allowing for new water transport pathways.

Volcanism poses a greater problem for a repository at Yucca Mountain than seismicity. Though the likelihood of an explosive volcano erupting directly beneath the repository is remote, the outcome would be devastating, spewing radioactive material directly into the atmosphere. More likely would be a scenario in which magma intersects a repository tunnel (not to be backfilled by design), and the associated heat, corrosive gases, and water would affect the waste packages, increasing corrosion rates and thereby releasing radioactivity into the environment much sooner than expected.

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[1] Civilian Radioactive Waste Management System Management and Operating Contractor (1999) Geology/Hydrology Environmental Baseline File, Department of Energy, B00000000-01717-5700-00027 REV 01, DCN 1, June 1999.

The rocks that make up Yucca Mountain are volcanic in origin and formed between 11.6 to 13.5 million years ago.[2] These rocks are composed of tuff, a fine-grained rock formed from cemented ash and rock fragments. The region was affected by three episodes of volcanism since 4 million years ago: one at 3.7 million years ago, one at 1 million years ago, and one at 80,000 years ago. These episodes have left volcanic cones and lava flows adjacent to Yucca Mountain. Though the 80,000-year event suggests that volcanism may be continuing, it is difficult to make precise predictions due to small number of volcanic cones or lava flows on which to base evaluations.

Partly as a result of the lack of evidence, the Nuclear Regulatory Commission (NRC) and the DOE have not yet come to agreement about the likelihood of future volcanism at Yucca Mountain over the 10,000-year time of compliance set out in the old EPA standard.[3] Extending the standard out to one million years, as the EPA has proposed, will vastly increase the uncertainties associated with our understanding of the probability of future volcanism.

Besides the potential for future volcanism, the "dryness" of the Yucca Mountain site weighs heavily on the suitability of the site. The repository at Yucca Mountain is to be located about 200-300 meters below the ground surface and 200-300 meters above the water table. The Yucca Mountain region is arid, receiving only 17 centimeters of precipitation a year. The idea behind locating a repository in the unsaturated zone, above the water table, was to take advantage of the assumed slowly-flowing water in the rocks. The DOE asserts that the average infiltration rate of water in the unsaturated zone is about 5 millimeters per year.[4] In such a location, the DOE assumed that little water would come into contact with the waste packages and corrode them over the millennia.

In the mid-1990s, the discovery of bomb-pulse tracer isotopes affected the models of water transport in the unsaturated zone at Yucca Mountain. Scientists at Los Alamos National Laboratory found unusually high values of chlorine-36 in the repository-level rocks at Yucca Mountain. High values of chlorine-36 result from nuclear weapons tests over the Pacific Ocean conducted in the 1950s. Because of these tests, chlorine-36 was put into the atmospheric circulation and carried eastward until it was precipitated out in places like Nevada. The implications for the repository are that water traveled 200 – 300 meters down in less than 50 years, at rates many times higher than the average infiltration rate used by the DOE. These fast pathways appeared to be associated with fault zones and fractures in the rocks.

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[2] Carr, W.J., Byers, F.M., and Orkild, P.P. (1986) Stratigraphic and Volcano-Tectonic relations of the Crater Flat Tuff and Some Older Volcanic Units, Nye County, Nevada. U.S. Geological Survey. Professional Paper 1323, and Sawyer, D.A., Fleck, R. J., Lanphere, M.A., Warren, R.G., and Broxton, D.E. (1994) Episodic Volcanism in the Miocene Southwest Volcanic Field: Stratigraphic Revisions, 40Ar/39Ar Geochronologic Framework, and Implications for Magmatic Evolution. *Geological Society of America Bulletin* 106, pp. 1304-1318.

[3] They are one order of magnitude off from each other in their probability estimates.

[4] Civilian Radioactive Waste Management System Management and Operating Contractor (1999), op. cit.

The DOE continues to study water transport in the unsaturated zone and has attempted to redo some of the studies done by Los Alamos, but these analyses were problematic. Questions remain as to which fractures may carry flowing water, what processes control fracture flow, and how water is partitioned between fractures and rock. In addition, the DOE has not included in its models of fracture flow events like thousand-year storms that would dump huge amounts of water on the land. Thus the DOE still has an incomplete picture of water transport in the unsaturated zone at Yucca Mountain.

Why all the focus on water? The problem is that it is difficult in the air-filled environment expected in the repository – an oxidizing environment – to prevent corrosion of the waste package and the spent nuclear fuel, the dominant waste form. All metals oxidize, just as iron turns to rust, so selecting a metal alloy for the waste package canister was challenging. The DOE has selected a material called Alloy-22, a chromium, nickel, molybdenum alloy, to form the outside layer of the waste canister. Alloy-22 is a corrosion-resistant alloy. The particular composition selected by the DOE has been in existence since 1981. Data from DOE laboratory tests of 6 months to 5 years in length have been extrapolated out to hundreds of thousands of years and suggest that the waste packages will begin to fail at 50,000 years.[5]

Once the waste canister fails, the spent fuel in its zirconium alloy cladding will be exposed to any water present. Spent fuel is basically uranium dioxide in addition to small amounts of fission products and actinides.[6] Uranium dioxide, as we know from natural analogues, is not stable in an oxidizing environment in the presence of water and it will alter, or rust, to form other minerals. It is not known whether these new minerals will retain the radioactivity.

One of the reasons that almost all other countries with repository programs are planning to use a wet or reducing (as opposed to oxidizing) repository environment is because spent fuel is stable in such under such conditions. As a result, by carefully selecting the repository conditions, these countries[7] have reduced the uncertainties associated with predicting future repository performance.

One final example of the complexity of the repository site is how the geochemical environment in the repository will evolve over time, especially the chemistry of the local waters. The DOE's strategy for Yucca Mountain is to emplace a large amount of thermally hot radioactive material into rock that contains water. Over time, there will be interactions between the thermally hot waste and the water and the rock, and the radioactively hot waste and water and

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[5] A recently published document suggests that the DOE has changed its analysis to find that waste package failure begins at 100,000 years hence. See Stahl, D. (2006) Drip Shield and Backfill, In A. Macfarlane and R. Ewing, editors, *Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste*. Cambridge, MA: MIT Press.

[6] Fission products such as cesium-137 and strontium-90 form from the splitting of uranium-235 atoms whereas actinides such as plutonium-239 and neptunium-237 form from the absorption of neutrons by uranium-238.

[7] These countries include Sweden and Finland, two of the countries with the most advanced repository programs.

rock. These thermochemical, thermomechanical, thermohydrological, and radiation interactions will produce processes and features that are impossible to predict in advance. Thus, we cannot really know the chemistry of the water over time or how it will interact with the waste package.

Uncertainty and Yucca Mountain

There are many uncertainties associated with trying to understand the behavior of a high-level nuclear waste repository thousands or hundreds of thousands of years into the future. One question we need to ask in siting a repository is whether the earth system is well enough understood to make predictive models of a repository far into the future? Is it possible to verify or validate these models? If not, then can one site a repository?

The DOE has argued that it has characterized all the relevant "features, events, and processes" at Yucca Mountain. I will argue that from my geologist's viewpoint that the DOE cannot know all the features, events, and processes it needs to describe the repository system because the repository is an evolving system whose basic thermodynamic and kinetic features are still not known. One example as just explained above is that of the evolution of the geochemical environment of the repository.

Perhaps our current Defense Secretary, Donald Rumsfeld put it best by noting in a 2002 press briefing, "There are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don't know we don't know." What we don't know we don't know could prove to be very important in the behavior of a geologic repository.

The DOE has attempted to predict the behavior of the Yucca Mountain repository over time using a complex computer modeling method called probabilistic performance assessment. The performance assessment of the Yucca Mountain repository[8] is made up of numerous submodels of systems that will affect repository behavior such as the climate, the unsaturated zone, the waste package, etc. The DOE has stated that it has validated these models by the use of laboratory tests, in situ tests, and field tests.

From the perspective of an earth scientist, it is not possible to validate or verify models of earth systems.[9] This is because earth systems are by definition open systems, accessible to exchanges of matter and energy. As a result, in open systems, it is not possible to know all the potential processes or input parameters that might affect the system. The Yucca Mountain repository is one of those open systems, and therefore it is not possible to legitimately validate the performance assessment model.

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[8] The latest version of which is in the DOE's draft license application, not available to the public.
[9] There is an excellent literature on this topic. Please see Oreskes, N., Shrader-Frechette, K., and Belitz, K (1994) Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences, *Science* 263, pp. 641-646, and Oreskes, N., and Belitz, K. (2001) Philosophical Issues in Model Assessment. In *Model Validation: Perspectives in Hydrological Science*, M.G. Anderson and P.D. Bates, editors. New York: J. Wiley and Sons, pp. 23-41.

Models of earth systems cannot be validated or verified by comparison to laboratory, in situ or field data for two reasons.[10] First, the data may have errors in it that while small now, over time may result in a large deviation from actual behavior. Second, though model results may predict current behavior, over time the geologic system will change in unpredictable ways, and therefore it is not possible to predict future conditions.

The terms "validate" and "verify" powerfully signify the truth of model results, suggesting that the model is an accurate representation of future behavior of the system. These terms are used to convince policymakers of the truth of the model results, though in actuality, the models cannot be validated or verified.

More disturbing is a practice, perhaps an unconscious one, in which experts present model results as if they were actual data. Secretary of Energy Abraham was guilty of such practice when he stated, "The amount of water that eventually reaches the repository level at any point in time is very small…" We have not and cannot measure the amount of water that will reach the repository at any time in the future, but the DOE generated a model of the amount of water that might reach the repository, which provided the results stated by the Secretary. These are not *facts*, but instead unvalidatable *model results*.

Scientists and engineers from multiple disciplines have contributed to the DOE's performance assessment model, making the results of submodels difficult to compare and fold into a meaningful overarching model. Given the different backgrounds of the scientists, engineers, and managers involved, it is possible that another set of participants might have produced a performance assessment model that gave divergent results. In fact, the International Atomic Energy Agency conducted a study of performance assessments and reached this conclusion.[11] In their study, six groups of scientists developed separate performance assessment models of contaminant transport in fruits. These models all produced differing results. The IAEA attributed the differences to the differing ways in which the modelers approached the problem, and the differing ways in which they implemented the models and selected parameters used in the models.

Why all the emphasis on performance assessment? The results of probabilistic performance assessment will be used by both the DOE and the NRC to determine the suitability of the Yucca Mountain site. They are forced to use these complex models for two reasons. First, there is only one site to evaluate, so it cannot be evaluated in a relative sense, as was the plan in the 1982 Nuclear Waste Policy Act (NWPA).[12] The 1987 Nuclear Waste Policy Amendments Act changed this strategy by allowing the characterization of only a single site, Yucca Mountain. Thus, the DOE and NRC needed to develop a method to evaluate the site in an absolute sense.

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[10] Please see Oreskes, N., Shrader-Frechette, K., and Belitz, K (1994) op cit. for a longer discussion.

[11] Linkov, I., and Burmistov, D. (2003) Model Uncertainty and Choices Made by Modelers: Lessons Learned from the International Atomic Energy Agency Model Intercomparisons. *Risk Analysis* 23, pp. 1297-1308.

[12] The 1982 NWPA had planned for three sites to be simultaneously characterized in depth, including the sinking of exploratory shafts to examine the subsurface.

They decided by the early 1990s that performance assessment modeling was advanced enough to apply to a geologic repository.

Second, the EPA standard calls for the DOE and the NRC to show that the site will meet a specific dose limit over a specified time period. To do this requires quantitative analysis, and thus the need for performance assessment modeling. Other countries have recognized the limitations of quantitative performance assessments, including France and Sweden. France has set a dose limit in its site standard, but does not make extensive use of performance assessment modeling and will evaluate compliance with the standard by using both quantitative and qualitative analyses.[13]

Sweden has stated that it will depend on performance assessments for time periods of up to 1,000 years, but for time periods beyond 10,000 years, "Although such long-term calculations should be performed, it is understood that with increasing time perspectives, quantitative results, with associated uncertainties, should be regarded as safety indicators. Using such indicators, it is recognized that the final risk assessment will involve a substantial amount of qualitative judgements [sic]."[14] Moreover, in terms of compliance with standards, the Swedes state that "it appears obvious that a strict comparison of calculation results with criteria is not meaningful. Calculation results, e.g., doses, with associated uncertainty estimates should be regarded as indicators of the level of safety and radiation protection achieved rather than dose predictions. Thus, it appears that 'reasonable assurance' is the only justifiable approach."[15]

Both France and Sweden recognize the limitations of performance assessments and the inability to determine compliance with standards by direct comparison with performance assessment results. They are comfortable with using a more qualitative approach. I would argue that the current U.S. performance assessment methodology is actually a qualitative approach masquerading as a quantitative one. In the current situation, what should the U.S. do to bring more clarity to its process to determine site suitability?

What Should We Do?

Given the strict limits placed by the EPA on the DOE and NRC's ability to evaluate the Yucca Mountain site and their inability to determine whether the numbers produced by the performance assessment models are valid, how should the United States determine the suitability of a repository site? I would like to make the following suggestions.

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[13] Garrick, B.J. (2000) Letter to Chairman Merserve on ACNW Visits to Nuclear Sites and Information Exchanges in the United Kingdom and France, May 15-19, 2000. Letter dated August 18, 2000. http://www.nrc.gov/reading-rm/doc-collections/acnw/letters/2000/1200158.html.

[14] From Nuclear Energy Agency, Radioactive Waste Management Committee (2004) RWMC Regulators' Forum: The Regulatory Control of Radioactive Waste Management Overview of 15 NEA Member Countries. Report number NEA/RWM/RF(2004)1, February 13, 2004, p. 139.

[15] Ibid, pp. 139-140.

• First, there is a natural opportunity to make changes to our system of site evaluation right now while the EPA standard is being reconsidered. Congressional legislation is not mandated to make the necessary changes; it can be done within the necessary agencies.

Once the EPA standard is promulgated, the NRC will have to adjust their regulations accordingly (currently 10 CFR 63), and the DOE will have to adjust their guidelines (currently 10 CFR 963). At this point in time, the NRC and the DOE can alter how they will determine site suitability and licensability.

• Second, in making changes to the regulations and guidelines, the NRC and DOE should move away from sole reliance on probabilistic performance assessment as the method to determine compliance with the EPA's standard and opt for a broader and more qualitative assessment scheme, similar to that of France and Sweden. One of the best ways to achieve assurance that the repository will contain the radioactivity over the long term is to reduce the uncertainties associated with waste disposal. For example, the DOE intends to operate Yucca Mountain at relatively high temperatures to maintain the tunnels above the boiling point of water for the first few centuries. This plan increases uncertainties about waste canister corrosion. Another example of reducing uncertainties is Sweden and Finland's plans to dispose of their spent fuel in a reducing environment, as opposed to U.S. plans to use an oxidizing environment.

• Third, the EPA may want to reconsider its standard in this mode. Currently, the United States uses a dose-based standard to govern nuclear waste disposal. Some countries, for example, do not use a dose-based standard at all. For instance, the United Kingdom uses a risk-based standard of one in one million per year fatal cancers from radiation. The National Academy of Sciences, in its 1995 report, suggested that the EPA adopt a risk-based standard, though the EPA ignored this advice.

•Fourth, work must continue on the Yucca Mountain site to determine whether it will be suitable as a geologic repository. To supplement the performance assessment, which would be useful only for short time periods (on the order of centuries), a comparative analysis can be adopted similar to that proposed in the 1982 NWPA. As it is not practical or pragmatic to select other U.S. sites and begin in-depth characterization for the purposes of comparison with Yucca Mountain, I suggest an alternative method. A large body of data exists for a number of investigated repository sites around the world. I suggest that this dataset be used for comparative purposes with Yucca Mountain. Included in the list of sites for comparison should be the Waste Isolation Pilot Project in Carlsbad, NM, which stores transuranic waste from the U.S. nuclear weapons complex, the clay site at Bure in eastern France, the crystalline rock site in Okiluoto, Finland, and the crystalline rock sites at Forsmark and Oskarshamn in Sweden.

•Fifth, if Yucca Mountain is found lacking in comparison to the above-listed sites, the DOE and the NRC may decide that it is not appropriate for use as a geologic repository. In this case, Congress would need to revisit repository siting and issue new legislation that allows the DOE to search for and establish new sites. It is highly likely that Congress will have to address this issue in the next ten years even if Yucca Mountain is approved by the NRC because it will not be able to contain all the waste produced in this country. In the United States, we are fortunate to have a large country with many geologically appropriate locations for a nuclear waste repository that have arguably simpler geology than Yucca Mountain. For a repository to succeed, the process must be fair and perceived to be fair by all participants.

A large amount of high-level nuclear waste already exists in the United States and requires disposal. This problem deserves rapid and focused attention. It is resolvable, but requires a delicate balance of technical prowess and fair and just policy-making. For the betterment of our environment, it is within our grasp to solve this problem.

Thank you for the opportunity to present my views.

Biographical Sketch

Allison Macfarlane is currently a Research Associate in the Technology Group of MIT's Security Studies Program and an affiliate of the Belfer Center for Science and International Affairs at Harvard University. She was most recently Associate Professor of International Affairs and Earth & Atmospheric Science at Georgia Tech in Atlanta, GA. She received her PhD in geology from the Massachusetts Institute of Technology in 1992. She has held the position of professor of geology and women's studies at George Mason University where she taught a wide variety of geology and environmental courses. She has also held fellowships at the Bunting Institute at Radcliffe College, the Center for International Security and Arms Control at Stanford University, and the Belfer Center for Science and International Affairs at Harvard University. From 1998-2000 she was a Social Science Research Council-MacArthur Foundation fellow in International Peace and Security. From 1999-2001 she served on a National Academy of Sciences panel on the spent fuel standard and excess weapons plutonium disposition. She currently serves on the Board of Directors of the *Bulletin of the Atomic Scientists*. Her research focuses on international security and environmental policy issues associated with nuclear weapons and nuclear energy. Her book on the unresolved technical issues for nuclear waste disposal at Yucca Mountain, Nevada, *Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste*, published by MIT Press, will be published in May 2006.