Yucca Mountain:
Science, uncertainty and political gridlock

In public affairs as in physics, the problem never holds still; it is always being redefined.
- Don Price (1981)

Introduction

The question of what to do about the increasing burden of nuclear waste in the United States has been a source of concern, uncertainty and disagreement for over half a century. Currently, the highly controversial proposal to store nuclear waste in a geologic repository beneath Yucca Mountain, about 75 miles north of Nevada seems on the verge of approval through the sheer will and inertia of the federal government, political and scientific uncertainties notwithstanding. The current stage of the debate has a long history of evolving science and politics around the issue.

This paper examines competing answers to the question, "should we store our nation's nuclear waste in a geologic repository beneath Yucca Mountain?" That technically and politically monumental question was first posed over 30 years ago, and remains open to this day. In our analysis we do not evaluate specific scientific claims for validity, relevance or legitimacy. In other words, we are not interested in who is "right" about what the science says or how science should be done with respect to Yucca Mountain. Instead we demonstrate the futility of that exercise, and then discuss ways in which scientific arguments have dominated and fueled seemingly unending debate. We then analyze two specific aspects of the controversy, with an eye to how uncertainty in science has contributed to this situation.

There is a pervasive assumption in politics and, perhaps, society at large that decisions should be rational and based on objectivity (Douglas and Wildavsky 1982). Thus, debates that involve large, complex systems frequently call on input from science, with the expectation that more "objective" knowledge about the systems will lead to increased understanding, improved decision making and the reduction of risk. In practice, however, the invocation of privileged, "idiomatic science" (Rose 1987) is often merely one of many *political* tactics used to back a value-based policy position. In fact it has been suggested that this is the primary role of science in highly controversial political issues (Collingridge and Reeve 1986). This begs the question of why science should occupy such a central role in the resolution of issues involving competing interests and values that do not fit in a framework of objectivity.

The assertion that decisions should be rational and objective, given the underlying reality of bias, uncertainty and the manipulation of information for political gain, yields a decision making arena in which the "excess of objectivity" (Sarewitz 2004) only exacerbates and prolongs debate. A problem with superficial reliance on objective, scientifically generated input is not that science occupies a major role in the process, but that it deligitimizes all other forms of debate. Thus subjective considerations still motivate actors on both sides, but they are hidden among technical arguments.

In our analysis, we examine the role of uncertainty in a setting where science is used to justify policy, and where conflicting assertions of what "sound science" says mire the debate. The first section of this paper traces initial motivations and scientific justifications that led to the selection and eventual singling out of the Yucca Mountain site. Although there were clearly political forces at work throughout this process, the public debate centered on a list of scientific criteria, including the dominant idea that waste stored in a geologic repository should experience low flux of water to remain secure or, in short, that "dry is good." Confidence among government scientists in this early criterion for justifying Yucca Mountain as a desirable site drove much of the scientific assessment of site viability, but its centrality to the case has become politically problematic in light of new information.

Second, we discuss the debate over the use and validity of models in predicting repository performance. For the federal government and specifically the Department of Energy (DOE), models have been integral in their efforts to advance understanding of natural and engineered elements of the Yucca Mountain repository. Both the federal government and its political opponents are aware that models are only approximations of the future. They are based on incomplete and imperfect understanding of natural processes (Oreskes et al. 1994), use principles that cannot be proven outside the laboratory (Cartwright 1999), and thus their projections are highly uncertain. On the other hand they represent the most advanced technical knowledge that can be brought to bear on the problem of nuclear waste storage in Yucca Mountain. Political debate has ensued over what models can actually tell us about the future, and whether this is information on which we should base our decisions, suggesting "reliability" as a more realistic measure of science than some abstract idea of "truth" (Ziman 1978, p. 2).

Throughout the debate, there has been a reliance on scientific evidence to justify political positions, a decidedly narrow approach to a question that could involve many social considerations. But the role of science has become so privileged that each side of the debate uses it as a primary source of argument. For example, an online document describing the Nevada State position on Yucca Mountain notes that the "controversy involves fundamental issues of a state's right to determine its economic and environmental future and to consent or object to federal projects within its borders" (Nevada 1998b). Yet despite this decidedly non-scientific framing of the issue, the ensuing argument completely ignores questions of state rights, and is instead based entirely around scientific uncertainty and risk.

The fact that seemingly objective results are mobilized by polar opposite interests suggests that perhaps the centrality of science has obfuscated elements that might otherwise bring better perspective and lead to a more "socially robust" solution. Socially robust knowledge can be seen as a new kind of scientific output that involves expanded participation by members of society and is less likely to be contested "outside the laboratory" (Gibbons 1999, Nowotny et al. 2001, Nowotny 2003). We argue that a major flaw in the ongoing scientific, bureaucratic and political process of developing Yucca Mountain as a suitable storage site for nuclear waste has been an unyielding adherence by both sides to the abstract ideal of objective scientific input. As Michael Gibbons (1999) has noted, a more practical view of science may be that of reliable knowledge, but even that is not enough. In highly public debate involving complexity, uncertainty and risk, decisions must account for much more than the results of scientific analysis and the opinions of a technical community. Yucca Mountain may or may not be scientifically defensible, but to move forward it must become socially acceptable as well.

Background

In February, 2002, after decades of controversy, President George W. Bush, at the recommendation of the Secretary of Energy, approved Yucca Mountain as a suitable site for a geologic repository. Though the event did not reduce surrounding controversy, it did set in motion a rigidly prescribed process that, objections by the Nevada State government and others notwithstanding, will soon lead to construction of the facility. DOE must now apply for a license to begin construction, to be reviewed by the Nuclear Regulatory Commission (NRC), which will apply standards set by the Environmental Protection Agency (EPA) for approval (EPA 2005b).

It has been argued that the site selection process for a geologic repository which eventually singled out Yucca Mountain and led to its current status involved elements of both science and politics (Metlay 2000), indeed, that the two were intertwined and co-evolving (MacFarlane 2003). But throughout site selection, evaluation and licensing debates, explicit arguments for and against Yucca Mountain have largely emphasized science, with politics and other social values kept in the background (Macfarlane in press). For example, the DOE's official online account of the "U.S. Approach for Permanent Waste Disposal" describes the justification of Yucca Mountain completely in terms of scientific analysis (OCRWM 2005b).[1] The NRC will review the license application in much the same terms, with little consideration for anything but technical analysis (NRC 2003, OCRWM 2005a).

The State of Nevada, the most vocal and relentless opponent to the Yucca Mountain repository, has many objections to many aspects of the project. These often take the form of accusations of mismanagement of bureaucratic process or the distortion or inadequacy of scientific evidence. Just as with DOE, however, any discussion of or objection to the dominant role of science is absent from the argument. For example, the opening statement of the most recent Report and Recommendations of the Nevada Commission on Nuclear Projects is typical in its implication that "good science" *should* be dominant: "Nevada has been at logger heads with the federal government over the unscientific, unfair, and heavyhanded way the U.S. Department of Energy has gone about the implementation of the program" (McKay

2005). Similarly, in a review of revised EPA regulations for radiation dosage, Robert Loux, executive director of the Nevada Agency for Nuclear Projects writes:

> Nevada concludes that EPA has no alternative but to withdraw the proposed rule and reissue a new draft standard that abandons the arbitrary and scientifically unjustified bifurcated radiation exposure limits… The only scientifically and legally supportable way to bring EPA's Yucca Mountain rule into compliance with the Court's directives and the NAS recommendations is to extend the 15millirem per year maximum exposure threshold, together with the 4 millirem groundwater protection requirement, through the period of maximum projected releases for the Yucca Mountain facility. (Loux 2005)

This argument is based largely on non-compliance with legal standards, yet nonetheless, science is invoked. Furthermore, the it implies that scientifically justified regulations are both possible and sufficient, going on to suggest a radiation limit that appears no less arbitrary than that currently used by EPA.

There is a massive amount of information on Yucca Mountain available from both Nevada State and federal sources,[2] much of it dealing with technical arguments about the site, its suitability, feasibility and legality. As we demonstrate below, this reliance on technical information is not a useful way to generate consensus on or social acceptance of high-level radioactive waste disposal in a repository beneath Yucca Mountain. The evasion (or ignorance) of social and political considerations misrepresents the true nature of the debate, setting the stage for considerable controversy and misunderstanding, which might be better managed by a more balanced approach.

Dry is Good

Of all the assumptions about the scientific basis for a good repository site, the oldest, most central has been that of water flux. This idea first emerged in a 1957 National Research Council Report produced by a group of geophysicists and geologists who (with the caveat that far more research was needed) recommended disposal of radioactive waste in salt deposits because "no water can pass through salt. Fractures are self sealing" (NRC 1957, p. 4).[3] Despite the many social, political and scientific concerns that are also quite important in questions of waste storage, the framing of a good repository as one that can stay dry has occupied the attention of scientists, politicians and evaluators ever since.[4]

Given that water has been identified as the most likely carrier of hazardous waste to the surface, "dry-ness," or low flux of water to and from the emplacement of waste was an obvious starting point for site selection. Early site evaluations focused on salt mines, with the logic that a large accumulation of salt indicates a lack of moisture (which would presumably dissolve any salt deposits) (Metlay 2000). However, political backlash over testing in an abandoned salt mine in Lyons, Kansas led to an expansion of geological scope, and many potential sites were evaluated. Part of this politically-driven shift led to a close scrutiny of sites where nuclear activity had already occurred, including Yucca Mountain (OCRWM 1998).

Although the re-focusing was related to both political and technical factors, explicit site justification remained purely based on scientific statements about each site under consideration. In fact, earliest arguments for the Yucca Mountain were couched entirely in geological and hydrological terms (two very particular subsets of science), asserting that the geology was ideal for maintaining dry-ness and isolation from surface water (OCRWM 1998). With this basis established in 1977, there ensued a massive amount of scientific study, all aimed at accurately characterizing the flow of groundwater in Yucca Mountain. The results of this work, which relied heavily on hydrologic models (discussed below), added increasing strength to the case. As percolation estimates dropped precipitously, researcher confidence soared, leading Donald Vieth, director of the Waste Management Project Office in Nevada, to include in his testimony before the U.S. senate the following claim:

> …it is not conceivable to me that we would discover something of a major nature that would cause us to change our mind about [Yucca Mountain]…. The processes of doing the modeling and the calculations that estimate the radioactive releases from the repository tells us that we may be five orders of magnitude below a very conservative EPA standard. (Nuclear Waste Program Hearing 1987)

In this moment, Vieth probably sealed the fate of Yucca Mountain (all other sites were eliminated from consideration shortly thereafter) (Metlay 2000), and neatly illustrated the folly of relying so heavily on uncertain and continually evolving science. For, several years after this political turning point, the estimates of water flux which led so convincingly to the selection of Yucca Mountain were thrown into serious doubt. Despite the fact that Vieth could not *conceive* of a major change in the science, sampling in the newly excavated Exploratory Studies Facility revealed traces of ^{36}Cl, or “the bomb pulse,” indicating that at least some water might travel from surface to repository at a speed orders of magnitude greater than had been previously predicted.

It is important to note that the irresponsible part of a statement like the one by Vieth, a respected scientist on the project, was his brash over-confidence, not the reporting of wrong results. Indeed, scientific ideas, especially those about natural processes occurring in open systems, often change in light of new information. However, scientists should recognize this ever-present possibility and present their results accordingly. Vieth did not. There is no reason to believe that the methods leading to the results were particularly “bad science.”[5] However, the assertion that nothing could change the situation is simply unscientific and obviously driven by an incentive to see Yucca Mountain approved as the nation’s nuclear waste repository. Ironically, however, Vieth was wrong about the estimates, but so far his political statement has proven right: even things "of a major nature," like the bomb pulse findings, have not caused DOE to change its mind.

As discussed in the following section, the bomb pulse findings and other revelations about the natural systems of Yucca Mountain have forced a new strategy for rationalizing Yucca Mountain feasibility, while still science-based, is a departure from the rationale that led to the site's selection. With a more balanced approach to characterizing and recommending Yucca Mountain for waste disposal, new understanding might not have resulted in such a political nightmare.

Dry is… irrelevant?

The revelation that Yucca Mountain may not be so dry, or at least that local hydrology was not very well understood, forced a re-thinking of repository design and the balance between geological and engineered barriers. Glossing over the blow dealt to earlier flux estimates by the ^{36}Cl data, an Office of Civilian Radioactive Waste Management (OCRWM) report notes that "testing of [the Exploratory Studies Facility] has led to substantially increased knowledge and understanding of the rock properties and hydrologic characteristics of the geologic formation in which the repository would be constructed" (OCRWM 1998). This is true, but it has also led to a completely new basis on which to justify siting the repository at Yucca Mountain – a shift which, to some, suggests political, non-scientific motives for keeping the repository there.

The new strategy, announced by DOE in 1996, combines various models and measures of natural and engineered repository elements into a single model (discussed below) (OCRWM 1998). The use of a more comprehensive approach to ensuring repository safety might seem more robust, but to opponents of Yucca Mountain it is sheer hypocrisy. In particular, the shift is seen as a way to mask information that, according to earlier criteria, would reflect poorly on the suitability of the site. The prior emphasis on geology and hydrology, now minimized, has become fodder for arguments against the facility, and it is often the leading argument in statements made by Nevada state officials (Nevada 1998a, 2003). For example, in response to the announced intent of Secretary of Energy Spencer Abraham to recommend Yucca Mountain for approval by president George W. Bush, an irate Nevada Governor Kenny C. Guinn notes the potential illegality of the shift from geological criteria to the “newly improvised [TSPA] approach to nuclear waste storage at Yucca Mountain, an approach that appears designed to ignore the blatant unsuitability of the geology at Yucca Mountain”(Guinn 2002). Nevada sued the DOE over precisely this shift in 2001 (Hiruo 2001).

It is debatable whether something as uncertain as percolation flux over thousands of years should be a primary indicator of suitability, but it is the changing logic of justification over the last two and a half decades that reflects poorly on DOE. The narrow approach of relying on “dry is good” was emphaiszed in the late 1970s apparently only because it strengthened the Yucca Mountain case. The new approach, which allows a much larger role for engineering, might be justifiable in and of itself, but, as many point out, it skirts the issue of geologic isolation that made up the original framework (Nevada 2003). However, those who argue this are equally guilty of picking and choosing their science. Even if effective geologic isolation could be irrefutably demonstrated (which, we argue below, is unlikely) this would be as arbitrary a way of framing the problem as total system performance. Why then, should a repository location be disqualified or certified solely on that basis?

In the end both sides base their arguments on “sound science,” but neither on conclusive science. Thus they have reached an impasse. Locked in a regulatory environment where non-science has been deligitimized, each side is forced manipulate and select among the science to back its own purely political stance, while exploiting the uncertainty that pervades the arguments of the other. As is already evident (Nevada’s veto of President Bush’s recommendation of Yucca Mountain was overridden by Congress), the winner may be the one with the most powerful politics, not the most convincing or more valid science.

Modeling

… the establishment that a model accurately represents the ‘actual processes occurring in a real system’ is not even a theoretical possibility. – Naomi Oreskes (1994)

As noted above percolation flux tests in 1996 revealed groundwater moving much faster than previously believed. This led to an emphasis on engineered barriers to perform tasks of which scientists had believed natural barriers to be capable (MacFarlane 2003).

To test the effectiveness of this new approach combining natural and engineered barriers both the Nuclear Regulatory Commission (NRC) and the EPA have required a Total System Performance Assessment (TSPA) (OCRWM 2003). The TSPA itself is a model, one comprised of many other models including simulated behavior of engineered barriers (e.g. drip shields, waste packages), models pertaining to water flow in the unsaturated zone (UZ) and other geologic processes (Wilson and Ho 2002).

A new model in this case means a new measurement standard as well. Whereas earlier tests focused on percolation flux, the TSPA measures success by adherence to new allowable EPA toxicity dosages of 15 millirem/year for the first 10,000 years of repository operation (EPA 2005a). Needless to say this shift has provoked a political fight over its scientific merits.

The federal government argues that increased understanding of repository geology produced the need for a new standard of measurement. Additionally, incorporation of several geological and engineering models creates a more accurate portrait of performance than an individual assessment of water percolation rates (MacFarlane, 2003).

The concept of "defense in depth" is one of the reasons DOE Secretary Spencer Abraham believes "sound science" backs the TSPA method. In the DOE's characterization there are four natural barriers (surface soil/topography, rock layers above and below the repository and rock and soil layers where the drinking water aquifer is located) and five engineered barriers (drip shield, waste containers, spent fuel cladding, waste form, and drift invert) constituting a nine layer system of defense (NEI, 2001). The rationale of this approach allows for individual failure of any one (or possibly more) of the nine barriers without a fatal breakdown in system containment.

The state of Nevada objects to the straightforward depiction of a nine-layer system, as if there were simply nine consecutive barriers to system failure. In their view, the DOE's depiction of "defense in depth" suggests that for nuclear waste to escape there would have to be a breakdown in all nine of the barriers, inspiring false confidence and ignoring inherent uncertainty. But this misrepresents the way complex systems have been observed to fail. Failures do not occur in a linear, consecutive fashion but through unexpected chain reactions in "tightly coupled" systems (Perrow 1999). Indeed, in this particular system the projected relative performance of each barrier is very unbalanced, with the engineered barriers now accounting for over 99% of system performance (Loux, 1999, MacFarlane, 2003).

First in Nevada's arguments is the concern that metal alloy containers and shields may not be up to the task. A troubling feature of the C-22 alloy (the material used to encase the radioactive waste) is that estimates of its performance are based upon a best case assessment of their durability. And obviously, there are no long-term test results to consult to determine whether those materials can hold up over thousands of years (Ewing, 2002).

Whenever these barriers do degrade the "defense" would then shift to a natural barrier—the dilution of radionuclides in the aforementioned underground aquifer—whose potential performance is completely uncertain (Nevada 1998a). The upshot of these two critiques, as Nevada, MacFarlane and others have noted, is that the TSPA is really a tool to mask individual deficiencies of a future repository that might damage it politically.

A major supporting claim about the Yucca Mountain repository is that "conservative" modeling estimates increase the validity of individual models that make up the TSPA, and thus the TSPA itself (Kraft 2001). In this way modeling results are less likely to underestimate potential radiological consequences. This approach contains several assumptions, one of which is that a conservative or "pessimistic" calibration of values does not sacrifice model accuracy. Assuming the worst conditions in modeling scenarios would seem to be a mirror image of later "optimistic assumptions" technique of extrapolation that Rodney Ewing and Macfarlane (2002) and others criticize as unreliable. It is unclear that skewing model data away from our best estimates or most accepted values is a sound method of increasing confidence in model projections.

Another federal claim is that the data compiled are comprehensive, or at least adequate to create a simulation faithful to reality. The government has apparently concluded that it has reached this status as evidenced in statements from Abraham that twenty years and four-billion dollars in research are sufficient to place high confidence in models (DOE 2002). There is no scientific justification that "x" amount of money or "y" years of research lead to proportionate reductions in uncertainty, least of all in an unprecedented undertaking such as this. Indeed, after approximately 15 years of research a singular 1996 test led scientists to fundamentally revise their estimates of percolation flux. Rather, Abraham's claim is a political argument in which lots of science is converted into "sound science" by decree of a highly ranked politician.

Abraham's claim that we have come far enough in scientific understanding of the site is no more valid than Donald Vieth's 1987 testimony before Congress (Nuclear Waste Program Hearing 1987). It paints an inaccurate picture of what scientific knowledge (which, as we have seen, is always evolving) can bring to a complex problem. As discussed above, rather than conclusive truth, it is more usefully measured in its reliability, or in the confidence it inspires. However, Abraham makes no reference to this idea; he sticks to the science as though it represents objective truth.

Even granting for the sake of argument that knowledge of the current geology of Yucca Mountain is sufficient for the tasks of modeling, opponents of the proposed repository in the Nevada government (Loux 2005, Guinn 2002) and in academia (Ewing and Macfarlane 2002) make the fundamental argument that models are simply unable to predict the future of a Yucca Mountain repository.

The DOE believes that, "Using advanced software and high-powered computers, scientists and engineers are also able to project how a Yucca Mountain repository for spent nuclear fuel and high-level radioactive waste is likely to behave" (OCRWM 2003). Skeptical state officials remember how estimates of percolation flux have changed, the constantly evolving state of knowledge at the repository, and now a shifting standard for approval. Given this history of scientific instability, the state of Nevada argued that these predictive models have little grounding in site data (Nevada 1998a). Scientific inquiry surrounding the potential site is primarily geological and, as Naomi Oreskes (2000) points out, geology is an explanatory science of singular events, different from sciences that deal in patterns and repetitions, and thus ill-suited to prediction.

Because humans never have comprehensive or perfect information about complex systems, input parameters rely on incomplete data, idealized formulations of, say, percolation flux, and theory based assumptions (Oreskes et al. 1994). As a matter of logic, models cannot truly validate an open system. The theoretical possibility of an unknown factor or alternative system behavior confounds actual validation. A model may produce the desired results (as the TSPA has) but this is really only a measure of the internal consistency of the model and the quality of input parameters and system hypotheses (Oreskes et al. 1994).

A case in point of these criticisms was the discovery of ^{36}Cl in rock samples taken from the mountain in 1996. Before this discovery, percolation assumptions about Yucca rocks resulted in flux estimates ranging from .02-1.0 mm/yr (Metlay 2000). If one test can so dramatically change modeling assumptions then any legitimacy models have may be in question. This is a perfect example of the incompleteness of the original models, and raises questions about whether we can ever know just how complete our model is. Combining numerous models into a single TSPA “super-model” only compounds this type of indeterminacy.

The debate over the scientific merit of the TSPA highlights the political use of science and the scientific wiggle-room and uncertainties that abound when models are employed. The DOE has asserted that the TSPA is a “robust” assessment of all of the relevant factors in repository performance, hence the name *Total* System Performance Estimate. It has further justified this relatively new approach as "sound science" based upon "defense in depth" of proposed engineered barriers coupled with pessimistic (conservative) estimations based upon mounds of data.

The state of Nevada has criticized the details of the TSPA, noting that individual failures that used to threaten site viability have effectively been hidden in this new standard. They have also persistently argued against reliance on models, based on past failures and their built-in limitations, as Oreskes and others have commented.

The Way Forward

Our analysis of the uncertainties and controversies that plague the Yucca Mountain repository provides much insight into the nature of this problem. We have seen how the criterion of dryness for site selection evolved from a source of scientific confidence and in Yucca Mountain into a liability. We have shown how the use of models to predict repository performance can raise as many questions as it seeks to answer.

An emergent theme is that there can be no purely objective answer, no definitive "science" of nuclear waste disposal and no solution that will please all interested parties. Some problems are simply too complex for science alone to answer. More importantly, the preceding discussion has revealed that, even though the debate over Yucca Mountain is at least as political as it is scientific, value-based arguments are absent from the public arena. In light of scientific indeterminacies, political spats, and the rigid framework that now defines the approval process, the question is, how to proceed?

Arguments tend to recommend one of four categorical policy choices: to proceed with the planned Yucca Mountain site, to place a kind of moratorium on Yucca Mountain licensing protocol and engage in efforts to resolve outstanding scientific concerns (Ewing and

Macfarlane 2002), to choose another site or even a method for disposal, or the status quo (storage at multiple temporary sites).

The idea of leaving nuclear waste to accumulate at temporary sites throughout the country has few vocal supporters, and for good reasons. Temporary sites are by definition just that—temporary. They presuppose an eventual solution that places the waste elsewhere. Temporary sites are also less secure than a permanent site would be, and harder to defend against accidents or sabotage. As Isaac Winograd (1990, p. 1292) asks, “Why was geologic disposal of HLW initially proposed over three decades ago? It was, of course, an attempt to preclude (or at least minimize) accidental or mischevious contact of humans and animals with HLW now and in the future.”

Choosing another site for disposal is likely to result in similar political deadlock unless a completely different approach is adopted. As noted above, politics were decisive in the selection of Yucca Mountain over other potential sites, but the Nevada repository also emerged because of its highly promising geology. Choosing a new site would not solve any geological or political problems; on the contrary it would set back disposal efforts by decades as scientists and politicians would have to repeat the same process in a different area. The same argument applies to the more creative alternative proposals to bury it in the sea, into ice sheets, or to blast the waste into space (Winograd 1990).

Placing a hold on the process seems an attractive choice, but a moratorium on the approval of Yucca Mountain is actually a kind of fool’s gold. Proponents of a pause argue that a delay would give time to increase site knowledge, build public confidence, and resolve the outstanding technical and scientific issues that cause concern. But nothing in the accumulation of knowledge about the site thus far has suggested that increasing technical knowledge eliminates uncertainty, builds confidence or resolves conflict. By itself, a moratorium is just "science as usual." Our knowledge of the repository has grown greatly over the two decades of study, yet all concede that comprehensive knowledge is unobtainable; a few more years of study will not change this fact. It is also unlikely that the implacable political opposition of Nevada officials will abate without federal efforts to build trust among Nevada stakeholders. The costs of delay are prohibitive: the project is already 12 years behind schedule and further delays are projected to cost $600 million each year. Furthermore, leaving the waste at 75 sites around the country places a great strain on security efforts (Winterfeldt 2002).

The prudent decision then, is to continue to move forward with research, licensing, and construction at Yucca Mountain. If the scientific uncertainties Yucca Mountain faces cannot be eliminated they must be managed; if stakeholders are skeptical, efforts must be redoubled to win their support. But efforts to do this through scientific study have failed.

Therefore we propose a robust staged approach that emphasizes flexibility, adaptability, capacity to continue learning (and the ability to incorporate new knowledge) and, above all, securing public support through increased stakeholder input. The latter will require an effort to include cultural and value-based concerns. This is less a policy change than a strategic approach to the existing policy. However it does involve a paradigm shift, one that recognizes the inadequacy of science, and is a departure from the normal adherence to objectivity.

Such a shift may prove unnecessary in the unlikely event that DOE manages to navigate smoothly the licensing process and any legal roadblocks introduced by Nevada. However, it could alleviate the political gridlock that has so prolonged the process.

This new approach would not require a wholesale revision of current efforts. By its nature the project cannot proceed all at once. The significant difference here is that at the end of each phase of the project the DOE would make its next decision based upon what it has recently learned rather than following a predetermined schedule "so that the ultimate path to success and endpoints themselves are determined by knowledge and experience along the way (NAS 2003, p. 1).

Especially if such "knowledge" and "experience" is conceived in social and procedural, as well as scientific terms, such a flexible approach might mitigate future political fights over methodological shifts such as the new TSPA. If the DOE adopted a policy of flexibility it could legitimately justify such shifts as a response to more than just unfavorable scientific results. In an undertaking where uncertainties are so high and irreducible allowing for mistakes and surprises is not only wise, it is necessary.

With our critique of modeling mentioned above, and the recommendation of a more flexible approach we are not arguing the abandonment of the TSPA. Rather, the role of modeling in general should be consistent with work that has shown how results can be relevant in a larger policy context. For example, the RAND corporation has developed a new approach to modeling for policy in which multiple model runs project numerous plausible futures as opposed to a single "best guess". In complex scenarios with "deep uncertainties," they argue, the best policy decisions should be effective over a range of possible futures:

> When applied to [Long Term Policy Analysis], the concept of robustness has several virtues. It provides a computationally convenient basis for identifying policy arguments that are true over an ensemble of plausible futures. It offers a normative description of good choices under the conditions of deep uncertainty and multiple stakeholders that characterize LTPA. (Lempert et al. 2003, p. 53)

If the TSPA or other modeling efforts could adopt such an approach, this might open up opportunities for "robustness" in terms of both scientific and other normative perspectives.

Critics of current scientific methods may argue that such models can be manipulated; while this is true, using models as an iterative, learning tool to achieve robustness and adaptability could unleash the potential of computer modeling.

Accomplishing public buy-in is perhaps the most important and difficult step in implementing our recommended approach. As Bruna De Marchi points out, "the purpose of a public debate is not to eliminate conflict but possibly to clarify what conflict is really about." So far DOE and Yucca Mountain scientists have defined the scope of the debate, possibly committing what De Marchi (2003, p. 171) describes as "type 3 error, [or], providing answers to the wrong questions and missing completely the relevant aspects because of inaccurate framing of a certain risk issue."

Fear of nuclear waste is high and trust in the federal government, especially in DOE, is low (Slovic et al. 1991). Nevada Governor Guinn, in his 2001 State of the State address, claimed that the repository is "the single greatest threat to the people of Nevada"(Guinn 2001). Public comment periods and technical progress reports on specific aspects of the process have proved insufficient in building the trust necessary to defuse the vicious political struggles that have marked this policy dilemma. We now know that building trust cannot be done simply by releasing technical tomes illustrating that the project is feasible (Slovic 1993).

DOE must prove itself to be an honest broker and reliable partner with the state of Nevada. Their justification for transporting large amounts of dangerous radioactive waste to the doorsteps of Nevada citizens must demonstrate not only scientific confidence and feasibility, but an understanding of the needs, fears and values of those who must bear the risk. Building trust is a long and fragile process, but in a democracy such as ours it is essential.

Notes

[1] One sentence at the end makes brief mention of the site's isolation from human populations, but there is no explicit mention of social considerations in the approval process.
[2] The best examples of this are, for the federal side, the Office of Civilian Radioactive Waste Management website (http://www.ocrwm.doe.gov/ymp/index.shtml) and, for the Nevada side, the Agency for Nuclear Projects website (http://www.state.nv.us/nucwaste/).
[3] Appendix F of the report, "Disposal of Radioactive Waste in Salt Cavities," by William Heroy, outlines other positive attributes of salt cavities, but "dryness" is the only argument used in the summary section of the report.
[4] Interestingly, the 1957 NRC report (p. 2) notes that answering the question "How shall we dispose of radioactive waste," is probably not possible until a site has already been designated, at which point questions of feasibility and methodology can be addressed. This seems to acknowledge limitations of science in site selection.
[5] Metlay (2000) notes institutional arrangements that may have led to smaller and smaller estimates of percolation flux and the over-confidence of project scientists, but this is more an issue of poor management by DOE than of *bad* science.

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