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ABSTRACT Nuclear waste disposal in the USA is a difficult policy issue infused with science, technology, and politics. This issue provides an example of the co-production of scientific knowledge and politics through public policy. The proponents of a repository site at Yucca Mountain, Nevada, argue that their decision to go ahead with the site is based on 'sound science', but the science they use to uphold their decision is influenced by politics. In turn, the politics of site selection has been altered by the scientific knowledge produced. Interestingly, changes in the scientific understanding of the site have forced policy-makers to look elsewhere for solutions. In the case of Yucca Mountain, they turned to engineering solutions that have, ironically, rendered any benefits of the site location superfluous. The Yucca Mountain example has significant implications for the ability of policy-makers to carry out an apparently democratic process for a science policy issue.

Keywords co-production, nuclear waste policy, regulatory science, technology policy

Underlying Yucca Mountain:

The Interplay of Geology and Policy in Nuclear Waste Disposal

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In 2002 there were landmark decisions by the US Federal Government on the issue of nuclear waste disposal. Over the next few years, the USA will continue to inch closer to a final decision on the Yucca Mountain repository, the high-level nuclear waste disposal facility proposed for the Nevada desert near Las Vegas.[1] The USA has been searching for a site to dispose of nuclear waste since the 1970s, at a cost of over US$7 billion. Much of that money was spent on scientific research on whether Yucca Mountain will be able to contain the waste for at least 10,000 years. Aiming these kinds of resources at the technical issue of whether Yucca Mountain is a suitable site for nuclear waste disposal should have produced top-notch science, but did it?

The Federal Government and its agencies – in particular, the Department of Energy (DOE) – have largely controlled the process of repository site selection and characterization. In doing so, they have claimed that their decision on the suitability of the site will be based solely on 'sound science'. Opponents of the Yucca Mountain site argue that the Government's decision is based purely on politics and that science has been

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abandoned in the decision-making process. Examination of this issue provides insight on how important science-policy decisions are made, and may lend insight into creating more successful policies.

The situation of nuclear waste disposal is unique in some respects. Because of the long time-span (tens of thousands to millions of years) of geologic processes that would deliver radioactivity to human beings and the environment, it is highly likely that we will never know if the repository 'worked'. The processes to be analyzed and evaluated in a geologic repository are complex and comprise a combination of scientific understanding of geologic processes and engineering design. They fit Perrow's definition of a normal accident waiting to happen, that is, tightly coupled events interacting in incomprehensible ways to produce an accident (Perrow, 1999). Because of the lack of predictability in the disposal of nuclear waste and the consequences of an accident or failure of the system, any proposed solution deserves serious consideration, not only from the technical and policy community, but from the science studies community as well.

Over the long and complicated process of determining site suitability for nuclear waste disposal, science, and policy – as promulgated and executed by the Government – have been involved in a feedback loop, whereby they have influenced each other to varying degrees. The main aim of the DOE repository project is to ensure that disposed nuclear waste (and thus, radioactivity) does not lead to the contamination of human beings and the environment. This task is very complicated, and the DOE relies on complex computer modeling to provide the answers. The models are based on empirical data, as well as expert judgment, assumptions about processes and parameters, and other computer modeling projections. The enormity of the modeling project provides ample scope for deconstructing the DOE's technical analysis and revealing the societal and cultural influences of the modeling outcomes (Gusterson, 1996; Miller & Edwards, 2001). The aim of the present paper, however, is different. I am interested in the influence of technical analysis on policy outcomes and the inverse, the role of politics and policy in creating science. The Yucca Mountain case contains multiple examples of such influence, and thus there is a case here for the co-production of policy and scientific knowledge as defined by Jasanoff (1996). Others have discussed the 'coupling' of experimental technology and politics (Shapin & Schaffer, 1985) and some, such as Donald MacKenzie, have pointed out that there is likely 'no categorical distinction to be made between the two [technology and politics]' (MacKenzie, 1990: 412–13).

Furthermore, I aim to show that in the case of policy that is science-based, even small changes in scientific knowledge can affect policy outcomes and vice versa. Indeed, Jasanoff has noted that science and policy are intimately tied to one another, as 'this unnatural union, an unstable policy instrument in which the balance of scientific and political considerations can disintegrate at any movement as a result of changes in either knowledge or politics' (Jasanoff, 1990: 8).

In what follows, I give an overview of the historical context and then consider the co-production of science and policy at Yucca Mountain through a few examples of how science and, more particularly, how changes in scientific knowledge affected policy for the Yucca Mountain repository. I also consider the opposite question of how policies and regulations concerning Yucca Mountain directed or influenced the kind of scientific analysis being done and the questions being asked. Such analysis provokes three questions:

(1) How does scientific knowledge about siting a nuclear waste repository become politicized and how should this relationship between science and policy be understood?
(2) What types of knowledge are used in making the policy?
(3) Who has framed the nuclear waste debate in the USA and what are the implications for a democratic decision on this issue? This paper will examine these questions in the context of a national policy decision in which science plays a starring role.[2]

Site Selection – Historical Background

Nuclear waste was originally created in the effort to make and then stockpile nuclear weapons during World War II and the Cold War that followed. The US Government first produced high-level nuclear waste as a by-product when it separated plutonium from spent nuclear fuel in a process called reprocessing. The plutonium was needed to power the country's nuclear bombs. The nuclear waste sat in large tanks, from where it has caused endless problems. The Hanford reservation in Washington, the Savannah River site in South Carolina, and the Idaho Chemical Processing facility in Idaho all produced high-level nuclear waste.

In 1954, the Federal Government passed the Atomic Energy Act, which paved the way for the commercial development of nuclear power. One consequence of the act was the increased production of nuclear waste. Nuclear energy development in the USA was allowed to proceed with little thought to the back-end of the fuel cycle and especially the waste. In 1957, the National Academy of Sciences produced the first report on nuclear waste (National Research Council, 1957), which took the view that nuclear waste disposal was essentially a technical problem. The report suggested that there were a number of ways to dispose of high-level nuclear waste (HLW), with the most promising being geologic disposal in salt formations.

From the start of commercial nuclear power, and for almost 15 years afterwards, little was actually accomplished on nuclear waste disposal. The Government began experiments on the suitability of salt for HLW disposal at an abandoned salt mine in Lyons, KA, in 1965–67. The waste produced by a 1969 fire at the Rocky Flats plutonium facility near Denver, CO, prompted more rapid action on HLW disposal. The Atomic Energy Commission (AEC) moved the resulting plutonium-contaminated waste to Idaho, which objected to being the recipient. As a result, the AEC promised to move it to a final disposal facility by 1980 (Office of Technology Assessment, 1985). Based on the previous research at the Kansas site, the AEC chose Lyons to host a nuclear waste facility, without, however, first obtaining local or state agreement. Within 2 years, in addition to local opposition, a number of technical problems arose. Questions arose as to whether the many boreholes over the salt mine could be effectively plugged, but the death knell for the Lyons site proved to be the disappearance of a large volume of water that was flushed into a nearby mine. The question remained as to whether that water could diffuse into the adjacent Lyons site in the future (Office of Technology Assessment, 1985).

By the mid-1970s the AEC had changed to the Energy, Research, and Development Administration (ERDA), which began to consider disposal of commercial HLW. In 1975, ERDA began a multiple site survey of geologic formations in 36 states. At the time, ERDA was considering salt sites first, but had also 'started a search for potential repository sites on federal land, especially land where radioactive material was present' (Office of Civilian Radioactive Waste Management, 1998: section 1, pp. 7–8). The plan was to develop six pilot-scale facilities by 2000, but by 1980 the pace had already slowed, and the focus was solely on sites in Louisiana, Mississippi, Nevada, Texas, Utah, and Washington State.

Initially, the ERDA investigated a number of different rock types and locations at the Nevada Test Site (NTS), including granite and tuff. Although some preliminary tests on the effect of nuclear materials on granite were conducted on the Climax stock at the NTS (Patrick et al. 1981),[3] the stock is located in one of the main testing areas for nuclear weapons and eventually was not deemed a suitable location. Thus, the interest shifted to the southwest corner of the NTS, with initial emphasis on saturated sites, those beneath the water table (Flint et al., 2001b). With the discovery of fast water movement in the saturated zone, the US Geologic Survey suggested siting a facility above the water table in the unsaturated zone (Winograd, 1974). Because of the deep water table at Yucca Mountain, the location was promising for the disposal of nuclear waste.

In the mid-1970s another event proved crucial to the path of HLW disposal in the USA. In 1974, India diverted plutonium from its civilian nuclear program and used it in the detonation of a 'peaceful nuclear explosion'. The diversion of nuclear material from a nuclear power program caused the Federal Government, first under President Ford and then under President Carter, to rethink its policy on the reprocessing of spent nuclear fuel.[4] President Carter issued a new policy for nuclear energy in which he indefinitely deferred the reprocessing of spent nuclear fuel. The direct result of this policy was the build-up of spent fuel at reactor sites around the country. Cooling pools at reactors that were designed to hold only a minimal amount of spent fuel (the rest, it had been assumed, would be sent off to a reprocessing facility) were in danger of being filled to capacity.

Congress addressed the issue in 1982 by passing the Nuclear Waste Policy Act (NWPA), which mandated that spent fuel and defense HLW be disposed of in a mined geologic repository. The NWPA specified that the Department of Energy would characterize and manage the disposal sites, the Environmental Protection Agency (EPA) would develop standards for the sites, and the Nuclear Regulatory Commission (NRC) would be responsible for licensing the sites and enforcing the standards. According to the legislation, at least two sites would be constructed, one in the west and one in the east.

So began the not-in-my-backyard race by states to prevent siting. By 1986, the DOE had whittled its list of nine sites down to three: the Hanford reservation in Washington, the NTS, and Deaf Smith County, Texas. The NWPA mandated the simultaneous characterization of three sites. None of the states was enthusiastic about the prospect. In response to the tense atmosphere in Washington, Congress limited appropriations for further work on HLW disposal to non-site-specific research (Cotton, 2003). This action essentially stopped research on waste sites. The outcome of this situation was the 1987 Nuclear Waste Policy Act Amendments (NWPAA), which resolved the siting question by specifying only one site to be characterized for nuclear waste disposal: Yucca Mountain, Nevada. One apparent advantage of characterizing a single site was cost: it was much cheaper to investigate one site instead of three.

Why was Yucca Mountain chosen? It is difficult to separate the technical reasons from the political ones, although site proponents and opponents attempt to do just that. The DOE claims that the decision is technically based because: (1) Yucca Mountain is located in southern Nevada, an area known for its closed hydrologic basins; (2) there are long flow paths between the repository location and groundwater discharge points (springs, rivers); (3) the rocks at the test site are suitable for waste isolation and may even slow movement of radionuclides; and (4) the aridity of the test site area implies that there is a low rate of groundwater recharge and very little water moving through the unsaturated zone (Office of Civilian Radioactive Waste Management, 1998).

Critics argue that, in fact, Yucca Mountain violates a number of accepted criteria for nuclear waste siting. A report by the International Atomic Energy Agency (2003) lists four general criteria that an appropriate deep disposal site would exhibit:

- Long-term (millions of years) geologic stability in terms of major earth movements and deformation, faulting, seismicity and heat flow;
- Low groundwater content and flow at repository depths, which can be shown to have been stable for periods of at least tens of thousands of years;
- Stable geochemical or hydrochemical conditions at depth, mainly described by a reducing environment and a composition controlled by equilibrium between water and rock forming minerals;

- Good engineering properties that readily allow construction of a repository, as well as operation for periods that may be measured in decades. (International Atomic Energy Agency, 2003: 6)

Yucca Mountain is located in a region known for its tectonic activity – both seismicity and volcanism. Its most recent earthquake (magnitude 4.4 on the Richter scale) occurred in June 2002, and from the top of Yucca's ridge crest one can spot relatively young volcanic cones in the valley just to the west. Furthermore, Yucca Mountain does not have the desired hydrochemical conditions listed earlier, but instead has just the opposite, oxidizing conditions. I will focus more on this last point later in the present paper.

Politics probably played as significant a role as science in the selection of Yucca Mountain, and the site was appealing to policy-makers in a number of ways. First, Yucca Mountain is located on Federally-owned land. The NTS, Nellis Air Force Base, and the Bureau of Land Management all own portions of the potential repository.[5] By using Government-owned land, Congress avoided the sticky problems of having to buy land from private owners or convince states to give up portions of their land. Furthermore, the adjacent land and groundwater were already contaminated by years of above- and below-ground nuclear weapons tests. Finally, Nevada is a politically weak state. It has a tiny population, an attribute seen as good for a nuclear waste site: the further such a facility can be sited from population centers, the better. Such a small population also leads to political weakness, and in the case of Nevada, this was especially so, as Nevada had only two junior senators in Congress when the NWPAA was enacted. Senator Harry Reid had just been elected for the first time in late 1986 and Senator Chic Hecht was elected in late 1982. They wielded little power in the Senate.

Site opponents are convinced that politics, not science, was the deciding factor in site selection. The non-governmental organization, Institute for Energy and Environmental Research, states plainly in a fact sheet: 'History illustrates that Yucca was chosen based on politics, not science'.[6] Politicians who oppose the site agree. Representative Edward Markey of Massachusetts states:

> Congress added insult to injury with enactment of the 1987 amendments to the Nuclear Waste Policy Act, which abandoned any pretense of exploring multiple sites to ensure that selection of a permanent waste repository would be based on the soundest scientific footing, and only after a full-scale review of all the options and all the available data on safety, environmental, and public health concerns. Instead, the Congress made a political decision to limit the search for a permanent nuclear waste dump to the Yucca Mountain site – thereby taking the remaining 98 Senators and 433 Representatives off the hook and handing the nuclear Queen of Spades to the State of Nevada. We then instructed DOE and the NRC to go forth and determine whether our political decision was scientifically supportable.[7]

In 2002, the DOE, with the backing of the President and Congress, overrode the State of Nevada's objections and overwhelmingly approved the Yucca Mountain site for a nuclear waste repository. The fate of the site is not yet final, however, but rests on the outcome of a license application to the NRC, to be submitted by 2004. Now I turn to examine in greater detail how science and policy interacted to produce the outcomes that we see today.

Interplay Between Science and Policy

In the course of the process of characterizing Yucca Mountain as a repository, changes in scientific knowledge affected policy and, in turn, political considerations influenced the kind of scientific analysis being done and the questions asked. In the following section, I consider a few examples of how science and, more particularly, how changes in scientific knowledge affected policy for and regulation of the Yucca Mountain repository. I then consider the opposite, how politics and policies concerning Yucca Mountain directed or influenced the kind of scientific analysis being done and the questions being asked. This analysis suggests that in the case of Yucca Mountain, scientific knowledge cannot be separated from politics and associated policies. Rather, they co-evolve in response to each other. To see the process in these terms alerts us to the possibility that other issues – technical and political – may have been by-passed. One can ask whether a different, perhaps more democratic process would have produced different scientific knowledge. I address this question at the end of the paper.

Changes in Policy and Regulation Resulting from Changes in Science

Initially, scientists working for the DOE made a number of assumptions about the future behavior of HLW in a geologic repository at Yucca Mountain. Here I use three examples to illustrate simple initial assumptions that later generated controversy with more scientific knowledge. Then I discuss the impact of these changes on policy as an example of co-production of knowledge and policy. In the first example, DOE scientists assumed that due to the low precipitation rate (15 cm/year) and the high evapotranspiration rate (95% of precipitation evaporates or is taken up by plants; Eckhardt et al., 2000), water would move at a very slow rate from the surface down to the repository level, located 300 m below. Initial estimates of the infiltration rate of water from the surface to the repository ranged from less than 0.5 to 4.0 mm/year (Flint et al., 2001a). In the mid-1990s the discovery of the presence of the ^{36}Cl isotope in rocks at the repository level suggested that this assumption incorrect. ^{36}Cl in groundwater resulted from atmospheric testing of nuclear weapons over the Pacific in the 1950s – a time-limited set of events that suggested that water traveled from the surface down through 300 m of rock in less than 50 years, much faster than previously thought (Civilian Radioactive Waste Management System, Management and Operations, 2000). This result indicated the existence of fast water pathways through the rock through which infiltration rates would exceed 80 mm/year (Flint et al., 2001a). This discovery caused the DOE to change its models of water movement through the mountain to account for fast water pathways. Although the mountain was originally thought to be 'dry', so that the type of material needed to encase the radioactive waste was not so important, it was now clear that potentially significant amounts of water could reach the waste packages and degrade them more quickly than previously thought.

Not only did it now seem that water had moved through the mountain much faster than previously thought, but there was also a problem for the future behavior of the mountain. Even more water could conceivably reach the repository during massive storm events that occur only every few thousand years (Fabryka-Martin et al., 2003). The future climate of the region may be wetter than now, potentially leading to even more water reaching the repository.

In response to ^{36}Cl results described earlier, the DOE has ordered more analysis. It is not satisfied with the ^{36}Cl data, though the academic community of hydrologists is quite satisfied with the research findings. As some of the scientists who collected the original ^{36}Cl data have stated:

> The finding of deep underground penetration of bomb-pulse nuclides [^{36}Cl] is largely accepted by the hydrologic community because of its consistency with many independent lines of evidence obtained in the field and in the laboratory. . . . However, fast movement of water and solutes through the unsaturated portion of the Yucca Mountain system has profound hydrologic implications, and therefore engendered further programmatic studies [by the DOE] to verify this result. (Fabryka-Martin, 2003)

In a second example, geologists studying Yucca Mountain initially believed that the rocks there, which are predominantly composed of tuff, a solidified volcanic ash, possessed the useful attribute of containing minerals that would retard radionuclide movement if and when radionuclides from HLW entered the saturated zone (Duguid, 1981). These minerals are called zeolites, and they can adsorb large cations – positively charged particles, such as cesium and strontium – which are among the most hazardous radionuclides in the repository. However, although zeolites are present and do adsorb these cations, owing to the short half-life of these particular cations and the good corrosion resistance of the proposed waste canister, it is likely that very few of these cations will be released into the saturated zone before they decay to other materials (Bish et al., 2003). Thus, the presence of zeolites in the rocks provides little added value. In addition, it is likely that heat from the waste will alter the adsorbing effects of other minerals in the surrounding rocks, such that they may not effectively adsorb other harmful radionuclides. Heating these minerals may, in fact, increase the water content of the rocks near the repository, which would result in more rapid transport of radioactivity (Bish et al., 2003).

A third example of a scientific assumption about Yucca Mountain that proved controversial with further research was that of the slow transport of actinide elements such as plutonium, americium, and curium. Plutonium is the most worrying of these materials because even tiny amounts are hazardous to human beings and the environment. It is present in relatively high quantities in the waste and is relatively long-lived. Initial research showed that the actinides, especially plutonium, were relatively insoluble in water. Scientists presumed that, if the actinides did escape from the waste package and contacted groundwater, they would not dissolve in the groundwater – and move from the repository area – but instead would 'stay put'. This assumption held until the 1990s, when research showed that these actinide elements attached to colloids, microscopic materials of organic or inorganic origin that behave as a solute (dissolved species) in water (Bates et al., 1992). Further research at the NTS showed that colloids are present in the local groundwater and do, in fact, transport plutonium over long distances (Kersting et al., 1999). No data on the formation of colloids, potential for colloid transport, or the amount of actinide expected to be released from the waste have yet been collected for Yucca Mountain. Many questions remain, but models of radionuclide transport in the unsaturated zone need to be refigured in light of these new data.

These examples show that DOE scientists' understanding of the geology of the site was increasing in complexity as more information was gathered. Increasing geologic complexity was accompanied by increasing uncertainty. Although the DOE previously thought the site had relatively straightforward geology, it actually had a very complex geology, which would affect the site's legal and regulatory status. To open and operate a repository in the USA, it must first be selected according to guidelines required by Congress and written by the DOE. Then, once the site is selected, it must receive a license from the NRC, according to that agency's regulations. The growing geologic complexity of the site threatened to disqualify it according to both the DOE guidelines and the NRC regulations.

Thus, changes in the scientific understanding of the behavior of the Yucca Mountain repository, illustrated in the examples given earlier, would be difficult to reconcile with the NRC's regulations promulgated in 10 CFR 60 and with the DOE's guidelines as spelled out in 10 CFR 960.[8] In 1996, however, the NRC proposed significant changes to its regulations, 10 CFR 63, which now base site evaluation entirely on a single performance assessment model, one in which models of subsystems are folded into a larger model (Nuclear Regulatory Commission, 1999).[9] As a consequence, uncertainties in the sub-models may be obscured by the larger analysis. The NRC defines the performance assessment model as 'a systematic analysis that identifies the features, events, and processes that might affect performance of the geologic repository, examines their effects on performance, and estimates the resulting expected annual dose [of radiation]'.[10] The success of performance assessment modeling assumes that one can identify all the features, events, and processes that would be significant over the lifetime of the repository, but that is another matter.

In its new regulations, the NRC deleted the siting criteria (10 CFR 60, Section 122), which, like the DOE guidelines, listed favorable and unfavorable conditions for siting a repository. Instead, the NRC replaced the siting criteria with requirements for performance assessment.[11] Given the changes to the DOE's understanding of the geologic and hydrologic systems at Yucca Mountain, it is quite possible that Yucca Mountain would not have met some of the criteria in the old regulations. For example, Section 60.122 (b) (3) of the old regulations states that favorable conditions are: 'Geochemical conditions that . . . (ii) inhibit the formation of particulates, colloids, and inorganic and organic complexes that increase the mobility of radionuclides'. Clearly, the discovery of colloidal transport of actinides and the presence of colloids in the similar geologic system at the nearby NTS suggest that Yucca Mountain rocks would form colloids that 'increase the mobility of radionuclides'. Another example of a criterion that might be violated is in Section 60.122 (c) (8): 'Geochemical processes that would reduce sorption of radionuclides, result in degradation of the rock strength, or adversely affect the performance of the engineered barrier system'. If the DOE uses a hot repository design, then heating may inhibit the ability of minerals in the surrounding rocks to sorb radionuclides.

Before the regulations and guidelines were changed, the plan was to find a site that had certain natural features that fit well-defined criteria. The change in the regulations and guidelines moved toward a system in which a site is selected, not quite randomly, and then a model is applied to see if, as an integrated whole, it meets pre-defined standards. The question is: Is one site evaluation method more open to political influence than the other? Is one method more 'objective' than the other?

The preselected criteria may be defined to fit politically-influenced notions of what a good site would look like. For instance, prior to Yucca Mountain's identification as a potential repository site, the type of rock that exists there, tuff, was not considered suitable for nuclear waste disposal. It is not mentioned in reports on waste siting. Once Yucca Mountain was identified, reports began listing tuff as a rock to consider when searching for a site. The reasons for using tuff as a repository material were the same as those for selecting Yucca Mountain as a site: both technical and political. In addition, complex computer models may be politically influenced. These models can be weighted in different ways, depending on the needs of the user. In this case, the DOE, the main user of the information, feels political pressure to find the Yucca Mountain site suitable. It is no surprise, then, that the performance assessment model relies on features of the site (in this case, only engineered features) that produce results that meet the standard. Thus, it seems both methods are open to political influence.

This is not the first time the NRC regulations were changed to accommodate scientific knowledge and political decisions. Originally, under the NWPA, the NRC regulations required the DOE to select a site located *beneath* the water table. Once a location *above* the water table was identified at Yucca Mountain, the NRC changed its siting regulations.

In 2001, the DOE accepted similar changes in its guidelines, eliminating the criteria section and replacing it with total system performance assessment analysis. As a result of these changes, the State of Nevada filed a lawsuit in which it contends that the DOE changed the guidelines to suit the data, implying that the Yucca Mountain site would have been disqualified under 10 CFR 960 (Hiruo, 2001). The DOE has defended its decision to make these changes by stating that the 'DOE proposes eliminating all individual disqualifiers, since maintaining them would mask how the system as an integrated whole would function'.[12] Elimination of specific standards on geologic features of the site and the move towards an evaluation of the system that integrates properties of the natural system with engineering features has resulted in a shift away from dependence on the geologic barriers and to a dependence on engineered features. According to the performance assessment results, more than 99.0% of the site's capability to preserve waste isolation is due to the performance of its waste canisters over the 10,000-year compliance period; only 0.1% is contributed by the geology of the site.[13]

Originally, geologic disposal was considered the best option for dealing with HLW because of the ability of the geologic environment to contain the waste for substantial periods (see for example, National Research Council, 1957). Engineered barriers such as the waste form and disposal casks were thought to be less reliable. The DOE has now reversed this previous thinking, so that in performance assessment analyses, geologic barriers such as slow transport, retardation of radionuclides, and distance of the repository from aquifers have been replaced by a greater reliance on engineered barriers such as the waste package and drip shield.[14] The DOE's own analyses support this shift and show that for the Yucca Mountain site, if the waste package were omitted from the performance assessment model, the radiation dose to people living near the site would reach 500 mrem (5.00 mSv) 2000 years after repository closure.[15] This dose would exceed the EPA standard of 15 mrem (0.15 mSv)/year by more than an order of magnitude. When the waste package is included in the model, peak doses of 800 mrem (8.00 mSv)/year are only reached 200,000 years after repository closure. Furthermore, the DOE's analyses of the effects of individual barriers to radiation dispersal at Yucca Mountain suggest the same conclusions: the largest dose increases result from failure of the waste package itself, and not from increased water infiltration into the repository nor increased transport of radioactivity in the water table (Office of Civilian Radioactive Waste Management, 2001).

The implications of the results of the DOE's performance assessment are that the geology of the site, over which much of the knowledge-gathering has been focused, no longer matters. Can this be true? Does the site not matter? If not, what was all this siting policy-making about? The solution to the growing complexity of the scientific knowledge has seemingly made the scientific knowledge itself superfluous. According to the DOE's current analysis, the solution to the nuclear waste problem lies in engineering design.

And what of the shift away from qualifying conditions and towards performance assessment modeling? The roots of probabilistic performance assessment lie in safety analyses for nuclear reactors. Performance assessment was developed originally by nuclear engineers to characterize the behavior of a totally engineered system (a nuclear power plant) with a lifespan of 40 years. It is being applied to a complex natural system (a geologic repository) over a time scale of more than 10,000 years. Engineering technology dominates scientific characterization of the site[16] at Yucca Mountain in two circumstances: first through the use of performance assessment to evaluate the site and second through the engineered feature, the waste canister, whose performance supposedly outdoes the geology of the site. But instead of using engineering technology to make his case, the Secretary of Energy stated that his decision to support the Yucca Mountain site was based on 'sound science'. Mark Rose has pointed out that in the past, engineers used the 'idiom' of science to elevate their status: 'In general, engineers invoked science, inter alia, as part of effort to secure funds, legitimacy, prestige, and markets' (Rose, 1987: 4). For the DOE, though scientific knowledge has taken a back seat to engineering design in analyzing site suitability at Yucca Mountain, the only way it can legitimize the analysis is through the idiom of science.

Redirection of Science from Political Needs

As I argued earlier, the selection of the Yucca Mountain site was guided as much by political needs as by scientific knowledge. Given this situation, what is interesting is the effect of the political choice of the site on the scientific knowledge gathered to support the suitability of that site. The most representative technical issue to illustrate the influence of politics on science is that of the 'dryness' of the repository.

The main technical reason DOE provides for regarding Yucca Mountain as particularly appropriate for HLW disposal is the low water table and the thick unsaturated zone. But as I pointed out earlier, this was not always the case. Initially, the DOE considered using the saturated zone at Yucca Mountain but changed its mind, in part due to the discovery of the existence of rapid water transport in the saturated zone. As a Los Alamos National Laboratory report on Yucca Mountain states:

> Two key reasons for studying Yucca Mountain as a burial site for nuclear waste are its dry climate and deep water table. The first minimizes water that could seep through the repository. The mountain's low water table enables building a repository that is deep underground (300 meters) yet still in the unsaturated zone, well above the water table. (Eckhardt et al., 2000: 468)

The key to nuclear waste disposal in the USA has become disposal of waste in a setting that minimizes contact with water. Put simply 'dry is good'.

Where does this belief come from? Although 'dryness' is held up as a scientific criterion for nuclear waste repository siting, scientific knowledge has not forced the move towards the unsaturated zone. In fact, most other countries, partly due to geological or hydrological conditions, are planning to dispose of their nuclear waste in the saturated zone below the water table. As long as an isolated saturated zone can be found that does not communicate with other aquifers, a saturated zone offers technical advantages, especially if most of the HLW is in the form of spent fuel (as will be the case for the USA). Reactor fuel is composed of uranium oxide, UO_2, which is stable and not prone to corrosion under reducing conditions, where little to no oxygen is present – conditions, in other words, that would be found in a wet environment. Oxidizing conditions (circulating air), like those expected at the Yucca Mountain repository, cause spent fuel to become unstable and break down, just as iron rusts in air. The breakdown of the spent fuel creates new minerals and increases the surface area over which any water present can act to remove radionuclides from the spent fuel. Sweden, for instance, plans to use copper as a canister material to encase spent fuel. Copper, as we know from its existence in nature, is highly resistant to oxidation and corrosion if it remains in a reducing environment. Thus, Sweden will considerably reduce the uncertainties in repository performance by emplacing its waste in a wet environment.

There is an analogy here to the situation discussed by MacKenzie (1990) in his analysis of the development of missile guidance systems by the USA and Soviet Union. His study showed that the engineering of missile guidance systems was not uniquely determined by technical constraints, but rather was to some degree socially constructed. The USA and the Soviet Union were both able to develop guidance systems, though using different technologies. Similarly, nuclear waste repositories in a number of alternative designs are possible and the selection of one as the best and safest possible design is equally socially constructed.

Alone among nations facing the problem of repository design, the USA is planning on a dry repository, even promoting the dry location and design as an essential part of the plan. The DOE has constructed this narrative of 'dry is good' to support its decision to site a repository in what others might deem an inappropriate location. Thus, it was important to overcome some of the negative aspects of the site (tectonism) and play up unique aspects of the site (dryness).

Another outcome of the 'dry is good' policy is a reorientation of research in the field of hydrology. Before the middle 1980s, hydrological research focused on water resources and aquifers. With the need to understand how water would travel from the earth's surface to a repository and then down an additional 1000 feet (305 m) to the water table at Yucca Mountain, a new area of research into the vadose zone was created. Large sums of money were made available to DOE researchers to gather data – more money than the field had seen before. According to the National Academy of Sciences, the Yucca Mountain project 'accumulated a significant body of knowledge applicable to fractured vadose zone [hydrological] models' (National Research Council, 2001: 11).

Not only has the Federal Government become convinced that 'dry is good', but so have anti-nuclear groups. In opposing the Yucca Mountain site, Public Citizen, a Washington DC-based non-governmental organization stated: 'One of Yucca Mountain's supposed advantages is slow travel time of water through the ground. Studies suggest, however, that water may move through the mountain at rates faster than once thought'.[17] The implication is that keeping the waste dry is the objective and water is the enemy.[18] These environmental groups have committed to the 'dry is good' view in this instance.[19]

As these anti-nuclear groups see it, a repository should be 100% dry, which is different from the DOE's understanding of 'dry'. In the DOE's analysis, it acknowledges that some water will reach the waste canisters, but they predict that the amounts of water will be low and will not be enough to significantly degrade the waste canisters. The concept of 'dry' in the Yucca Mountain case is an example of what Salter has called an 'essentially contested concept' (Salter, 1985). It has become one of the focal points around which the suitability of the Yucca Mountain site is debated. Because the underlying assumptions about the concept of a 'dry' repository are so different (and therefore the definition of the concept is different), it will not be possible to resolve debates between DOE and anti-nuclear groups on this issue.

Science, Policy, and Politics at Yucca Mountain

From the discussion in the present paper, we have seen examples of both science forcing policy changes and politics simultaneously circumscribing the limits and expanding the direction of scientific investigation. The process of nuclear waste disposal siting in the USA, therefore, is not a straightforward one of science guiding policy decisions.

In the politically charged topic of nuclear waste disposal, we see that politics has affected science in repository site selection by forcing the science done to characterize the site to fit through the lens of the 'dry is good' policy. At the same time, US policy on nuclear waste disposal has changed in response to deepening complexities in the scientific knowledge of the repository site. Thus, scientific knowledge, politics, and policy have co-evolved in the case of nuclear waste disposal at Yucca Mountain.

Given this co-evolution of science and policy, one issue of concern is whether the full range of scientific and policy issues that surround waste disposal at Yucca Mountain have been adequately explored. For example, given the emphasis on a dry repository, has DOE done an adequate job assessing the potential problems with spent fuel in such an environment? Or has it overlooked this issue in its efforts to find evidence in support of the 'dry is good' policy? Have the US siting policies been too restrictive in response to scientific ideas about the type of site that would be suitable?

The magnitude of the policy and regulatory changes that resulted from deepening complexities in the science suggest that the original policies and regulations that guided repository siting were too restrictive and inflexible. To see this more clearly, we can look at other countries' experiences. The Finnish HLW disposal program, though much smaller than that of the

USA, serves as an interesting example. To date, it has been more successful than the US program. The emphasis in the Finnish program was on the siting decision, not on a detailed repository design, as in the USA (Vira, 2001). Finland thought it important to compare several alternative sites in making a final decision instead of making an absolute decision on a single site, as is the policy in the USA. Finland decided that the value of comparing sites was in presenting to the public the relative advantages and disadvantages of all sites. They have now decided on a single site – though this is only a 'decision-in-principle' and allows both the government and the local community to back out of the decision. Thus, Finland has employed a flexible HLW disposal decision process.

Finland chose a waste disposal policy that, unlike the US policy, separated the siting decision from that of repository engineering design. In the Yucca Mountain case, it has become clear to the public, and in particular the State of Nevada, that DOE is changing its policy to suit the scientific results – so much so that now, to make the site suitable, DOE must invoke engineering aspects of the repository (the waste canister), which have no intrinsic relation to the physical site itself, to make the site suitable. Thus, perhaps what the Finnish example shows is that to make a repository site more palatable to the public, it is important to make a strong case for the geographic location on more 'scientific' grounds. In the next section, I begin to explore this issue of democracy and siting.

Knowledge, Democracy, and Policy

If scientific knowledge, politics, and policy have co-evolved, is it still possible to have a democratically acceptable nuclear waste repository? To answer this question I will first deal with the questions of who produces the knowledge, who uses it, and what is produced. Then I will address the larger and more difficult question of whether different knowledge would have been produced had the policy process been different.

By now it should be clear that scientists who work for DOE produce the scientific knowledge that underpins (or perhaps does not) nuclear waste policy in the USA. Some of these scientists work directly for DOE, but most in fact are employed by contractors to the DOE. These contractors include large multinational corporations like Bechtel, SAIC, and TRW,[20] but also include scientists at the National Laboratories and the US Geological Survey. These scientists are not the ones that frame the issues, however. That is done by the Federal agencies, including the DOE, the NRC, and the EPA, and Congress. To a lesser degree, the National Academy of Science and the Nuclear Waste Technical Review Board do some of the framing of questions.[21]

The science produced to dispose of nuclear waste can be termed 'mandated science' (Salter, 1985) or 'regulatory science' (Jasanoff, 1990), science 'produced for the purposes of decisionmaking' (Salter, 1985: 37). Research science, known to scientists as 'basic science', is distinguished from regulatory science in a number of ways. Research science is conducted for the most part at universities, and the products of the research are published in peer-reviewed journals; the work is judged solely by peers. Regulatory science, on the other hand, is done by government and industry bodies, the work is not published in journals, but collected together in reports. Peers judge the work to a small degree, but scientists and the knowledge produced remain accountable to Federal agencies, Congress, the Courts, and the media (Jasanoff, 1990).

Jasanoff (1990) describes the content of regulatory science as having three components: knowledge production, knowledge synthesis, and prediction. Knowledge production yields information relevant to regulation, knowledge synthesis results in screening and evaluating the knowledge produced, and finally the knowledge produced is used to make predictions about the risks involved in the procedure requiring regulation. These elements apply directly to Yucca Mountain, where scientific knowledge is being produced to address the question of whether the site is suitable for waste disposal. A whole new field of science, hydrology of the vadose zone, has even been created to meet this goal. The knowledge itself is being used to predict the behavior of the repository over geologic time through meta-modeling to determine whether members of the public could be at risk over that time. Finally, the knowledge produced at Yucca Mountain is being evaluated not by scientific peers so much as by DOE managers, who are required to meet goals set by their agency.

It is the last point at which politics appears to play a direct role in the knowledge produced. The scientists producing the knowledge to be used in nuclear waste policy must satisfy their managers at the DOE. And these managers, in turn, must fulfill legal and regulatory obligations under the NWPA, NRC and EPA rules. In this way, not only do the managers at the DOE and its contractors seek particular knowledge – politicized knowledge, if you will – but the scientists themselves internalize this politicization to some degree and address questions and gather and interpret data in a way that fulfills their political obligations.[22] Thus, the scientists themselves become proponents of the Yucca Mountain site. Their sense of being aligned with Yucca Mountain site supporters only increases when site opponents attack them.

The DOE has tried to cross the boundary between regulatory science and research science by claiming that the science used to support its decision on Yucca Mountain was 'sound science'. The framing of scientific knowledge as 'good science', a term used within scientific circles to designate the standard, acceptable level of knowledge produced,[23] attempts to place scientific knowledge created in a politicized setting into a de-politicized one.

The DOE's efforts not withstanding, the knowledge produced in the nuclear waste policy process remains clearly in the field of regulatory science. The scientific research produced at Yucca Mountain is published in the form of 'gray' literature. Unlike reports produced by research science, many of the DOE reports are unsigned – 'authored' instead by the institution, not an individual. Such authorship obscures accountability and decreases scientific debate. In the case of research science, journals often publish reviews of papers that take issue with the results or interpretations of data presented in previously published work. The scientists themselves carry out public debates in journals. In the case of the science produced at Yucca Mountain, the scientists who produced the knowledge are only rarely accountable to the larger scientific community. Furthermore, the results of this research are not widely distributed because of the difficulty of obtaining the reports.[24] As DOE scientists themselves have remarked:

> It is important to note that the history of the characterization of Yucca Mountain cannot be accurately reconstructed solely on the basis of citable literature. To fully understand this history requires reference to unpublished draft reports, memoranda, and rough notes. (Flint et al., 2001b: 49)

What constitutes peer review in the case of scientific knowledge produced for Yucca Mountain? All DOE contractors require that completed scientific research go through an in-house review that not only considers the quality of science done, but also the implications of making certain findings public. In this way, scientists are responsible to managers who may or may not be scientists themselves, but who have clear political agendas to meet the goals and requirements of the DOE, NRC, and EPA. Salter points out that some peer review comes in the form of public hearings (Salter, 1985), and this is the case for Yucca Mountain, though the impact of the feedback from public hearings and public comment is negligible. These public comment exercises appear to be more like 'rituals' than serious venues to receive, process, and incorporate input from the public.[25] Finally, some peer review comes from entities such as the National Academy of Sciences (when asked) and the Nuclear Waste Technical Review Board, whose influence depends on the members of the board and, since they are appointed by the President, is politicized. Clearly, as Jasanoff (1990) has pointed out, regulatory science is accountable to political entities and therefore is politicized from the start.

The users of the knowledge produced at Yucca Mountain are numerous. The Federal agencies and Congress are the main users, since they mandate and manage the process of knowledge production. Other users are the public, defined here as the State of Nevada, which clearly has a unique investment in the outcome of nuclear waste disposal policy, local, national, and international anti-nuclear groups, and the rest of the US public. Some individuals in the larger US public will be interested in the policy outcome because either they live near a nuclear power plant or nuclear weapons complex site that temporarily houses nuclear waste, and/or they live near a transportation route to Yucca Mountain. Interestingly, the DOE and other agencies define the users of the scientific knowledge as 'stakeholders', a term that seems to privilege the DOE (it does not define itself as a stakeholder) and serves to sharply demarcate knowledge producers from users.

What do users of this knowledge expect of what is produced? Simon Shackley and Brian Wynne pointed out that 'decision makers and advisory scientists believe that policy ideally should rest on reliable, robust, and hence certain scientific knowledge' (Shackley & Wynne, 1996: 275). They argue that policy conflict results from scientific uncertainty: reduce the uncertainty and the policy is strengthened. Furthermore, they argue that although knowledge producers may acknowledge uncertainties in scientific data, the users sense that it is more certain. The ^{36}Cl data, which I discussed earlier, have been used by opposing sides in the nuclear waste debate in quite different ways. Anti-nuclear groups and the State of Nevada used these data to underscore the unsuitability of the site, because of the evidence that it was no longer absolutely 'dry'. I have argued that the DOE has changed its policy in response to this knowledge. Essentially, the Los Alamos scientists, in producing the ^{36}Cl data, increased the uncertainty about the future performance of the repository by calling into question the amount of water that would reach the supposedly 'dry' repository. In being forced to publicly respond to these data, the DOE has ordered more data collection and analysis to redo the original study, though they are careful not to repeat the Los Alamos scientists' exact methods of data-gathering.[26]

The DOE is not the only group to desire certain scientific knowledge; the public does as well. The ^{36}Cl data provided more fuel for the State of Nevada's case against the Yucca Mountain site. In a 1998 report, the state of Nevada noted:

> The discovery of atmospheric nuclear bomb-pulse chlorine-36 in fracture coatings in and below the Exploratory Studies Facility at the Yucca Mountain site has provided convincing evidence that infiltrating fluid moves rapidly through fractures in Yucca Mountain from the ground surface to the water table. This is in direct conflict with the DOE's original unsaturated zone flow model and has caused the DOE to change its model from one depicting flow dominated by very slow movement through the rock pores to one in which rapid fracture flow dominates. The State has been advocating and developing such a model for a number of years and, as a result has determined that the Yucca Mountain site cannot meet the groundwater travel time requirements of the DOE's Part 960 siting guidelines and NRC's licensing rule, 10 CFR Part 60.[27]

Not only are the ^{36}Cl data the basis of a complaint against the DOE, they are also the basis of a lawsuit against the Federal Government.

This brings us back to the question of whether a different policy process would have produced different science. I think, from the analysis earlier, that the answer is yes. To begin with, if the political process had not limited the selection to very few sites – and then to one site – a broader scientific view could have been incorporated. The Finnish case is one example. Germany under the Social Democrat–Green Government provides another example, with its recent decision to change its approach to nuclear waste disposal.[28] Under the previous Christian Democrat Government, Germany had selected the Gorleben site for a nuclear waste repository, in a strategy similar to that of the USA: decide on one site, do some scientific analysis to see if it suitable, do not involve the public in the decision. Under the new Government, it 'threw out' the Gorleben site and began with a 'white map' to re-examine the entire country for appropriate sites. The first 'cut' at this project will only consider sites on the basis of scientific criteria, not political ones, such as the geologic conditions of the site. The scientific criteria by which the site will be selected are divided into two steps – the first step using general scientific criteria, the second step using a weighting process that employs somewhat more detailed criteria. In contrast to the criteria used initially in the US site selection procedure, these criteria are not set up to qualify or disqualify sites; they are all allowed, but weighted. Once at least three sites have been identified as being technically suitable, then the public enters the site selection process. At this point citizens of the selected regions, who all along will have had access to the scientific process that occurred previously, will be able to vote on whether to allow the Government to explore the proposed site. Their vote will also be informed by socio-economic studies of the positive and negative impacts of a waste repository on the region.[29] Thus, the German process may have a better chance than the US one at using a broader scientific view.

The site selected and the science to support the selection may have been different under different policy objectives. The NWPAA, in selecting only one site to be studied for its suitability as a nuclear waste repository, put a large amount of political pressure on the DOE to find that site suitable. In fact, analysts who have observed the evolution of US nuclear waste policy doubt that Congress could approve another site (Carter & Pigford, 1999). Therefore, the scientific knowledge produced to support the policy must fit the bill or be thrown out (or redone, as the case may be). If the USA had characterized three sites simultaneously, as originally planned under the NWPA, then there would have been much less pressure to find a particular site acceptable, though the pressure would have remained to find at least one of the sites acceptable.

What Lessons Can the USA Learn?

Since I have been examining an issue that has significant implications for US citizens (and those of other countries by example), I want to draw some practical suggestions from my analysis. Has the current policy process on nuclear waste disposal produced an acceptable outcome? I think we cannot answer this question yet because we do not know whether the US nuclear waste program will succeed or fail. A number of important decisions have yet to be made. As presently structured, the US program will face many hurdles, including lawsuits and NRC licensing approval. The DOE plans to continue to collect scientific data on the site as well. Certainly, the final story has not been written yet.

Nonetheless, perhaps we can ask a more detailed question: Is the knowledge produced acceptable to the knowledge users? And if not, then what can be done to address the situation? In other words, is a more democratic disposal policy possible? After all, even if all nuclear power plants were to stop producing electricity tomorrow, the USA would still have a significant quantity of nuclear waste. Somehow, an acceptable disposal policy must be developed.

Congress and the DOE seem satisfied with the science that upholds the decision to go forward with Yucca Mountain, though clearly, in the case of Congress, politics most likely dominated the selection of Yucca Mountain (most members of Congress voting for it not to be in their backyard). The DOE is not fully satisfied with the science they have produced because, although the Secretary of Energy has recommended the site to the President, the DOE is not yet ready to submit a license application to construct a repository to the NRC.[30] Thus, it must have some misgivings about the data it currently has. As we have seen, DOE is in the process of redoing some of the science produced (the ^{36}Cl data). It now depends heavily on engineering analysis to evaluate the site and engineered features to prevent radionuclide doses to the public.

The State of Nevada sees each example of scientific uncertainty as another datum in its case against the Yucca Mountain site. In that way, it is perhaps satisfied with at least some of the knowledge produced, just not in the overall synthesis and analysis of the knowledge. Anti-nuclear groups fall into a similar camp as the State of Nevada. So, in the end, the main question about democracy and science policy may not be about the scientific knowledge itself, but how it is used to make and justify policies.

Scientific knowledge, politics, and policy at Yucca Mountain have co-evolved, each affecting the other, but this does not mean that we cannot use science to inform a successful nuclear waste disposal policy. We are still left with the fact that as a country we need a solution to the nuclear waste problem, preferably a democratic one in which the public has confidence. To carry out this procedure, there are certain questions about potential sites that only science can address. For example, one would not want to locate a site in shallow rock that is highly fractured with rapidly moving groundwater – that would be a recipe for immediate failure. So, scientific knowledge can provide necessary information for locating potential repository sites. In actuality, these sites are numerous – especially in a country as large as the USA. It is the politics that limits them. It would be a mistake, though, to depend entirely on science, because, as I have shown, the science itself is infused with politics. Better to openly invite public participation in site selection, perhaps according to the German plan.

On siting a repository at Yucca Mountain, the DOE has painted itself into a corner that will be difficult to leave. After touting the natural geologic features of the site to retain radioactive waste, the DOE has abandoned the geology for engineering design. It is now making its case for the site based not on the site itself – the natural geologic features of Yucca Mountain – but on the features that the DOE itself will build. The site, as such, no longer matters. The whole question that the DOE was to address, through its charge from Congress, was whether this particular site was suitable for a repository. It has not really addressed this question.

Perhaps a prescription that will find more success is a more transparent one, in which scientific analysis is made available to the public and the academic community for scrutiny, and the public has the opportunity to provide input throughout the process. Certainly, the policy of considering only one site is a recipe for disaster – political choices clearly are foisted on scientists in this way. A more successful policy – and one more acceptable to the public – would be to compare multiple sites and choose the 'best' site. But the 'best' site must be selected not only through scientific analysis. The local residents should also be given a choice. The German process will prove interesting to watch. The US policy may still result in success – if success is defined as putting waste in the ground. But the definition of success will be that held by one side in this process – the Federal agencies charged with this task, and the nuclear industry that is pushing for its completion.

Notes

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1. In 2002, the Energy Department and the Bush Administration recommended the site to Congress; the State of Nevada vetoed this decision and was overridden by Congress. Now it is up to the Nuclear Regulatory Commission to determine whether the site is licensable.
2. I would like to preface the analysis in this paper with a disclosure: I myself am a geologist and am involved in a scientific critique of nuclear waste siting in the USA (see, for instance, Ewing & Macfarlane, 2002). Thus, in some ways, I am analyzing my own prejudices and preconceptions.
3. A stock is a form of granitic-type rock.
4. Reprocessing creates separated plutonium, the material that powers nuclear weapons. By not separating the plutonium from the spent fuel, the high radiation from the spent fuel provides a barrier to theft and use in nuclear weapons. Spent fuel itself cannot be used as a nuclear bomb; plutonium must be separated out first.
5. Nevada holds the distinction of being the state with highest land ownership by the Federal Government: 86% of the land (Applegate, 2000).
6. Institute for Energy and Environmental Research, Takoma Park, MD, USA <http://www.ieer.org/fctsheet/yuccaalt.html>.
7. Rep. Ed Markey, US Congress, Press Release, 10 January 2002 <http://www.house.gov/markey/iss_nuclear_pr020110.htm>.
8. CFR stands for Code of Federal Regulations.
9. Note that though the rule change was initially proposed in 1996, it was not accepted until 1999.
10. See Office of Civilian Radioactive Waste Management (1999): 67064.
11. See Section 63.114, Requirements for Performance Assessment of 10 CFR 63, Nuclear Regulatory Commission (1999). Some scientists argue that the performance assessment criteria are less thorough and more open to interpretation than the original qualifying conditions. Others may argue that performance assessment itself is thorough; this is an ongoing debate in the scientific community. See, for example, Ewing (1999).
12. See Davis (1999). Even the NRC was critical of the DOE's proposed changes (Behrens, 1996).
13. Robert Loux, slide from his presentation, 'Relative Contribution of Waste Isolation Barriers', from a DOE presentation to the Nuclear Waste Technical Review Board, 25

January 1999, in Regulatory Information Conference 2002, Washington, DC, 6 March 2002.

14. The waste package refers to the nickel-alloy casks into which spent fuel or other HLW will be loaded. Drip shields are titanium alloy shields that will cover the waste package to protect it from rockfall and dripping water.
15. Bechtel SAIC Company (2001) 'FY01 Supplemental Science and Performance Analyses, Volume 1: Scientific Bases and Analyses', TDR-MGR-MD-000007 REV 00 ICN 01 (Las Vegas, NV: Department of Energy).
16. I am using engineering and science here as separate categories, although in general there is clear interdependence between the two (see for instance, Barnes, 1982). In the analysis presented here, 'science' pertains to the understanding of the natural earth system and its behavior through time. 'Engineering' pertains to systems constructed by man and placed into a natural environment.
17. From Public Citizen fact sheet: 'What's Wrong with Burying Nuclear Waste at Yucca Mountain?' <http://www.publccitizen.org/cmep/energy_enviro_nuclear/nuclear_waste/hi-level/yucca/articles.cfm?ID = 6256>.
18. It is interesting to note that MacKenzie (1990: 383) similarly found opponents adopting their foes' rhetoric. Nuclear weapons opponents made the same assumption that weapons proponents did: missile accuracy would increase with time and 'modernization'.
19. Wynne has noted the propensity of some environmental groups to remain convinced of realist epistemic views (Wynne, 1996).
20. At the moment, the DOE's Yucca Mountain Project is managed by Bechtel-SAIC.
21. The 1987 NWPAA set up an 'independent' review board for nuclear waste disposal, the Nuclear Waste Technical Review Board, whose members are selected by the President of the USA.
22. I have observed, in attending numerous scientific conferences with scientists who work for the DOE on Yucca Mountain, that DOE scientists (shall we call them regulatory scientists?) who present results do not follow the usual presentation format used by research scientists. They present the question motivating the research, the methodology they used to gather data, the data themselves, and nothing more. They do not offer interpretations of the data or conclusions about the impact of the data on significant policy issues (which is an essential part of research science). My impression was that they were not allowed to do so by their managers.
23. I take the term 'good science' from my own experiences as a scientist. During my training and after, my colleagues and I would use the term to approve and sometimes exalt a piece of work or a scientist.
24. For a while, the Department of Energy had available a number of the most recent reports on its Yucca Mountain website (<http://www.ymp.gov>), but since the 11 September 2001 attacks, they have removed all of these reports. Thus, it will, once again, be difficult to obtain them.
25. Wynne (1982) has discussed the inquiry into the plans to construct a spent nuclear fuel reprocessing plant in Cumbria, UK, as a 'ritual' instead of an exercise in democratic decision-making process.
26. Los Alamos scientist, personal communication (2002). (I do not want to name the scientist for fear of repercussions from his managers.)
27. Nevada Agency for Nuclear Projects (1998) 'State of Nevada and Related Findings Indicating that the Proposed Yucca Mountain Site is not Suitable for Development as a Repository', <http://www.state.nv.us/nucwaste/yucca/nuctome2.htm>.
28. Haury, Heinz-Jorg (ed.) (2002) 'Selection Procedure for Repository Sites, Arbeitskreis Auswahlverfahren Endlagerstandorte' (Committee on a Selection Procedure for Repository Sites, December).
29. Of course, the public may veto all selected sites. In that case, the government must re-evaluate the entire issue of nuclear waste disposal and must develop a new policy process to address the problem. One difference between the US and German political

systems may lead to different outcomes in each country: government in Germany tends to be fairly decentralized, while in the US, the Federal Government sets the controls.
30. By law, the DOE was to have submitted this license application within 90 days of Congress' vote to support the site. It now looks like it will not be ready to submit the license application until 2004.

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