NOTE

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Chapter 10

From Tin Roof to Torn Wet Blanket:

Predicting and Observing Ground Water Movement at a Proposed Nuclear Waste Site

by

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Introduction

In 1944, while producing the plutonium that eventually would devastate Nagasaki, the United States also generated in Washington state the first batch of high-level radioactive waste.[2] In the decades that followed, additional defense production facilities were built, and more than 100 commercial nuclear power reactors began to dot the landscape. The waste from both military and civilian uses of nuclear energy now lies scattered across 43 states in huge metal tanks, cylindrical glass logs, basins filled with water, and dry storage casks. The amount of waste likely to be produced in the next 30 years will be nearly twice what exists today. Finding a more permanent means of isolating all that radioactive material from people and the environment represents a formidable scientific, engineering, and political challenge.

A strong consensus prevails within the technical community that the most effective method for long-term isolation of radioactive waste is burial in a deeply mined geologic repository. A committee appointed by the National Academy of Sciences (NAS) advocated this approach as early as 1957 (NAS: 1957). Twenty-four years later, the United States officially selected geologic disposal as the preferred means of isolating radioactive wastes for thousands of years (DOE: 1981). Subsequently, many other countries – including Sweden, Finland, Belgium, England, Canada, France, Germany, Spain, Russia, and China – have adopted the same course.

What no country has done, however, is to *demonstrate* that the technical and political hurdles to building a high-level radioactive waste repository can be overcome at a specific site. For the United States, until that task can be accomplished, the policy objectives of safeguarding human health, protecting the environment, fulfilling the federal government's moral and legal responsibility for stewardship of the waste, and ensuring that significant risks are not exported to future generations will not be fully achieved.

This chapter traces how the U.S. Department of Energy (DOE), through its Office of Civilian Radioactive Waste Management (OCRWM), is developing intricate predictions of how a complex repository system sited at Yucca Mountain, Nevada, might perform for as long as 1,000,000 years.[3] I begin with a background discussion of why Yucca Mountain might be an appropriate disposal site, then narrow the focus to examine attempts at predicting one key parameter affecting repository performance: percolation flux, or the volume of water flowing through a unit area of rock per unit of time at the proposed underground repository horizon. I consider how those predictions have evolved over the last 15 years and try to explain those changes. Finally, I explore how the predictions had important public policy implications. More generally, however, I examine how scientists tried to understand and deal with predictive uncertainties in a hotly contested and politically charged domain.

Predicting Percolation Flux in the Unsaturated Zone at Yucca Mountain

Background

In a geologic repository, groundwater is the chief mechanism for transporting nuclear waste to the accessible environment. In light of this scenario, the 1957 NAS report argued that "abandoned salt mines or cavities especially mined to hold waste are, in essence, long-enduring tanks" (NAS: 1957, 5). Two factors make salt formations an appropriate and, in some sense, elegant, location for a repository. First, because salt is highly soluble in water, the existence of a salt formation suggests the absence of water. Second, should any fractures arise in the salt to compromise the isolation potential of the formation, they would soon be self-sealed because salt flows plastically under the high pressures found at typical repository depths. Intermittently over the next two decades, efforts were made to explore specific salt sites for a high-level waste repository; they all proved futile, stymied either by technical missteps or by political opposition.[4]

In 1979, the salt-centric strategy was overturned, and a new paradigm took its place. The Interagency Review Group on Nuclear Waste Management (IRG), established by President Jimmy Carter, and relying heavily on recent technical analyses (APS, 1978; USGS, 1978), concluded that the behavior of the host rock is *only one of many* factors that affect repository performance. Other important influences are:

- the waste form—either the unaltered spent fuel rods or the material, such as glass, within which the reprocessed waste is embedded;

- the waste package, which holds the waste form—this can either be simple, such as a thin-walled stainless steel canister, or complex, such as a thick-walled canister composed of several layers of material;
- the design of the repository structure—for example, the surface temperatures of the waste packages can be kept below or above 100º C for thousands of years; and
- the hydrogeological environment that surrounds the repository facility—i.e., the factors that control the behavior of the groundwater in and around the repository (IRG: 1978).

On the basis of this conclusion, the IRG cautioned repository developers that what matters is the *behavior of the disposal system as a whole*, not the behavior of any particular component in isolation.

This new, but hardly radical, paradigm provided the conceptual foundation for the 1982 Nuclear Waste Policy Act (NWPA). That law established a site-selection process in which at least five different hydrogeologic environments would be compared. The NWPA requires the DOE to set forth criteria for comparing sites. The three sites that best satisfied those pre-established criteria would be selected as the prime candidates for repository development (NWPA: Section 112). Nine environments were investigated early on, and this number was quickly reduced to the requisite five. The DOE employed sophisticated decision-aiding methodologies to reduce further the number of sites, and by 1986, only three locations – the Deaf Smith salt site in Texas; a basalt site at Hanford, Washington; and Yucca Mountain, which features volcanic tuff – remained in the so-called "horse race."

Although political considerations likely played some role in reducing the number of sites, it appears that a desire to examine locations having diverse geologies was more important. But with political opposition mounting in the states still in contention, with the cost of investigating each environment increasing dramatically, and with widespread anger at the DOE for unilaterally "postponing indefinitely" efforts to find a site in the eastern United States for a second repository, Congress in 1987 passed the Nuclear Waste Policy Amendments Act (NWPAA). Among other things, the NWPAA limited site investigations to Yucca Mountain unless that site was found to be unsuitable and Congress authorized the characterization of another site (NWPAA: Section 160(g)(3)).[5]

The selection of Yucca Mountain appears to have been driven by a variety of technical and political factors (Colglazier and Langum: 1988). The State of Nevada, for example, has claimed that the choice was dictated almost entirely by a hostile constellation of political forces that overwhelmed Nevada's three-person congressional delegation. This perspective notes that among those political forces in 1987 were the Vice President and the Speaker of the House, who were from Texas where the Deaf Smith site is located, and the Majority Leader of the House, who was from Washington where the Hanford site is located.

Although it would be naïve to discount political considerations in the passage of the NWPA Amendments, Yucca Mountain did appear attractive *technically* to many policy-makers, especially when compared to Deaf Smith, which overlay the huge

Ogallala aquifer, and Hanford, which is highly fractured and close to the Columbia River. Thus, while the scientific arguments that pointed to the suitability of the Nevada site likely were *insufficient* for its selection in 1987, those arguments were probably *necessary*.

Waste Isolation at Yucca Mountain

Several features of Yucca Mountain make it a potentially attractive location for a repository. Situated within a larger federal reservation, the site is isolated far from major population centers. It is also located within a closed drainage basin, so surface waters do not flow into major river systems. Yucca Mountain is in an arid environment, receiving less than 200 millimeters of precipitation a year, and there are no perennial streams nearby.

Initially, scientists envisioned constructing a facility more than 600 meters below Yucca Mountain's crest, deep within the saturated zone (SZ)—that is, below the water table, where groundwater moves continuously through pore spaces and fractures in the rock. On the basis of suggestions from the U.S. Geological Survey (USGS) (Robertson *et al.*: 1982), however, the DOE decided to explore the possibility of placing a disposal facility at a lesser depth, within the thick unsaturated zone (UZ), above the water table. In the UZ, water and gases are present in the pore spaces in varying proportions, but always at less than saturation, and the water either does not move at all through the pore spaces, or it moves extremely slowly. This new approach rested on the argument that the amount of water reaching the repository would be very small and that a repository could be designed so that any such water would pass into the permeable rocks below, with minimal contact with the canisters of waste.

An important study by Eugene Roseboom (1983) of the USGS more fully explained the advantages of storing the waste in the UZ:

- The UZ forms a natural barrier that can promote waste isolation. It thereby contributes to "defense-in-depth."
- The environment is relatively dry and should remain so for many thousands of years.
- The behavior of any water in the UZ is far more predictable than the behavior of water in the SZ.
- Predicting the effect of heat on water in the UZ is easier than predicting its effect on water in the SZ.
- Relatively simple engineering and design features can be developed to divert water from waste packages and to drain the water into faults and fractures.
- Emplacement of waste in the UZ makes access, monitoring, and retrieval much simpler.

At the same time, Roseboom noted two disadvantages. If climate change caused the water table to rise to the level of the repository, radionuclides would no longer be isolated. Moreover, if spent nuclear fuel were not reprocessed, gaseous radioactive isotopes of iodine and carbon could be released. Roseboom discounted both the likelihood and the seriousness of the two drawbacks.

During the following year, the DOE formally compared the advantages and drawbacks of locating a repository in either UZ or the SZ (Johnstone *et al.*: 1984). In its official discussion of the decision, the DOE observed that none of the horizons were unsuitable as a repository (DOE: 1986, 2-45 - 2-47). However, rock units in the SZ were effectively eliminated because they had either poor mechanical strength or high groundwater temperatures (Carter: 1987, 172). In the end, the DOE selected the Topopah Springs rock unit, a thick layer of volcanic ash and larger fragments that was "welded" into a strong, relatively impermeable rock—or welded tuff—because of the high temperature conditions under which it was deposited. The choice of the Topopah Springs unit departed from convention because it occurred at depths considerably less than the 700-1,000 meter depths usually envisioned for deep geologic repositories.

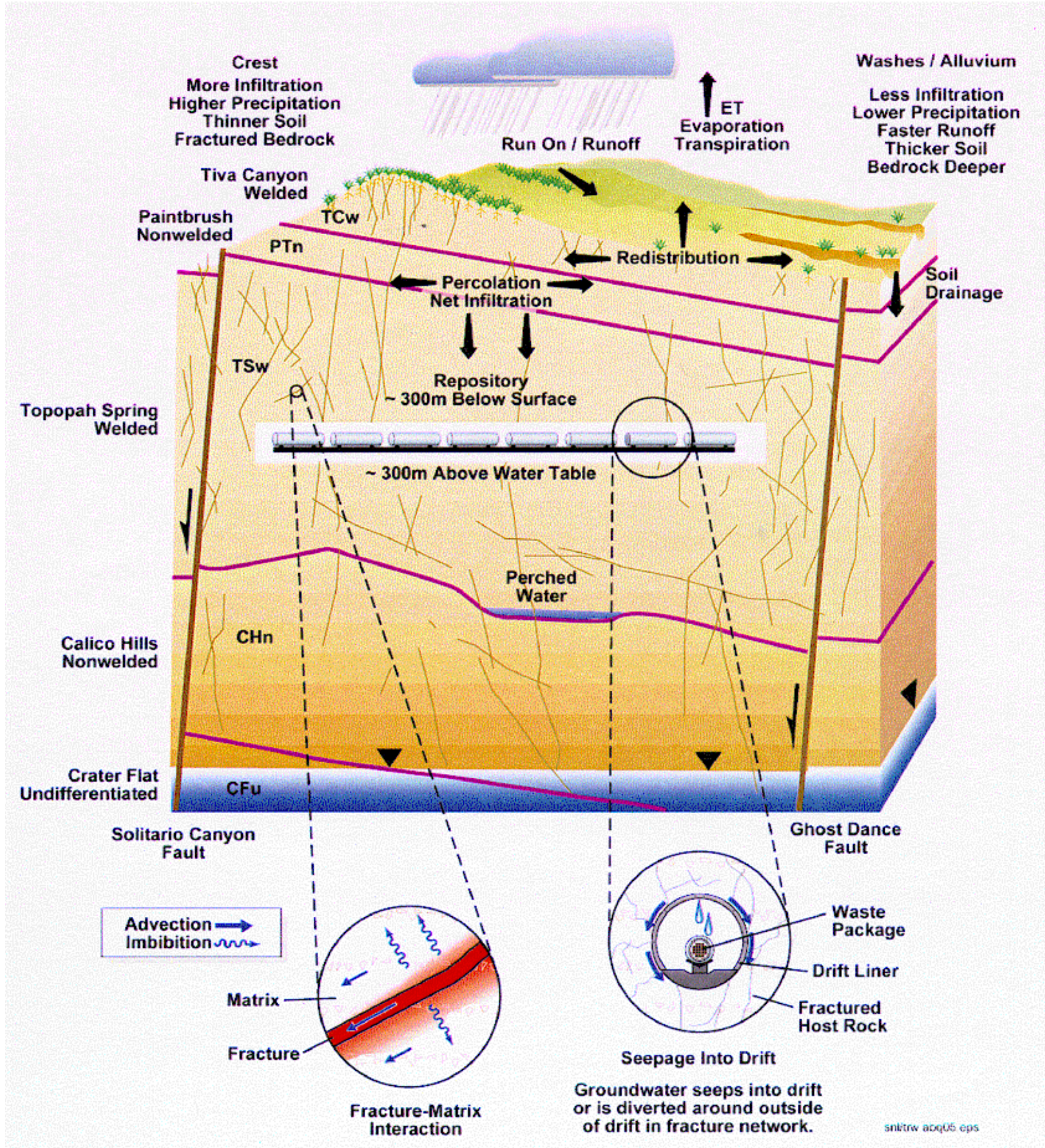
How Dry is Dry?

Percolation flux is one of the key parameters affecting the performance of a repository at Yucca Mountain. Water can percolate through rocks by moving through interconnected pore spaces and by moving along cracks and fractures. The higher the percolation flux, the more water will seep into the tunnels—or "drifts"—where the radioactive material is emplaced. Water in the repository has two potentially problematic effects. First, it can accelerate the corrosion of the waste packages. Second, the more water contacting the waste, the more likely that radionuclides will be mobilized and released from the repository.

Unfortunately, percolation flux cannot be measured directly because of the large scale and inaccessibility of the rock units involved, as well as the slow movement of water through those units. Thus, percolation flux is predicted from indirect measurements on rock samples in the laboratory as well as from mathematical models (NWTRB: 1991, 18-21). The remainder of this section describes how predictions of percolation flux at Yucca Mountain have evolved over time. In following the narrative, the reader may find it helpful to refer to Figure 10.1 below.

Roseboom's assessment of the UZ as a potential host for a repository benefited from the work of another USGS scientist, Isaac Winograd, who had spent many years at the adjacent Nevada Test Site investigating both the regional and the local hydrology to assist the DOE in constructing tunnels within which nuclear weapons tests were conducted. Although Roseboom never developed quantitative models to estimate the amount of water that might reach the repository horizon, his informal analysis relying on "expert opinion," suggested that a percolation flux of roughly 4 millimeters per year (mm/yr) was in the right ball park.[6] In particular, Roseboom was reluctant to characterize the UZ as "dry." He noted that water would flow along fractures, that water might very well drip onto waste packages continually, and that water could even pond within the facility, thereby coming in contact with a substantial fraction of a waste package's surface.

At about the same time that the UZ was selected as the reference repository site at Yucca Mountain and as the DOE was still investigating alternative sites in a half-dozen locations around the country, a study conducted by two other USGS scientists reached the following conclusions (Montazer and Wilson: 1984):



Source: DOE

Figure 10-1

- Average precipitation was somewhat higher than the 125 mm/yr suggested by Roseboom. It was probably closer to 150 mm/yr.
- Based on studies of other arid environments, net infiltration of rain water into the shallowest rocks above the repository site—the Tiva Canyon unit—probably averaged 0.4 to 4.5 mm/yr.
- The Paintbrush unit, which lies directly above the proposed repository, could act like an umbrella – or what investigators would later call a "tin roof" – and laterally divert up to 100 mm/yr of water away from the repository—water that would otherwise travel down toward the stored waste. The actual amount of diversion was unknown.
- A maximum of approximately 0.2 mm/yr of water could be flowing through the pore spaces, or matrix, of the Topopah Spring unit, where the proposed repository would be located. The flux in fractures in the rock, however, was not known.

Nonetheless, on the basis of the physical properties of the rocks, Montazer and Wilson believed that "…of the conservatively estimated 4.5 mm/yr net infiltration, probably only a *maximum of approximately 1 mm/yr* is transmitted through the Topopah Spring unit [emphasis added]" to the repository horizon.

Thus, Roseboom's 1983 prediction of a 4 mm/yr percolation flux was reduced the next year to 1 mm/year by Montazer and Wilson's research. How important is this 3-mm/yr difference? The performance of a repository built at Yucca Mountain will depend on the how much of the percolation flux seeps into the emplacement drifts and comes into contact with the waste. When the percolation flux increases, it "could cause *more than a proportional increase* in the seepage [flux] in the drifts" (NWTRB: 1998, 38; emphasis added). This nonlinearity arises because pores in the rock will locally fill with water until some threshold is reached, at which point the water will be able to move from the pores into fractures that lead into the repository. In other word, changes up or down in predictions of the percolation flux could produce *even larger changes* in predictions about seepage flux and, therefore, repository performance. The evolution of estimates about percolation flux needs to be viewed and understood from this perspective.

As the investigations by Montazer and Wilson were being completed, the DOE office in Nevada finished preparing a draft Environmental Assessment (EA), a key document in the site-selection process mandated by the NWPA (DOE: 1984). When final, the EA would become the foundation for choosing which three of the five sites still in contention would become the prime candidates for development into a repository. Citing the work by Montazer and Wilson, the DOE observed: "Despite the uncertainty about the exact conditions and processes of the hydrologic system at Yucca Mountain, especially in the unsaturated zone, the conservatism of the assumptions and the analyses allows confidence in the general conclusions [i.e., low percolation flux] about the hydrologic system" (DOE: 1984, 6-120). On the basis of those conclusions, the DOE projected that there would be *zero release* of any radionuclide to the accessible environment for the first 10,000 years after closure of a repository at Yucca Mountain (DOE: 1984, 6-247). The choice of a 10,000-year prediction reflected the expectation that the Environmental Protection Agency (EPA) would establish a 10,000-year period for regulatory compliance. This regulatory time frame is, of course, arbitrary and represents a policy judgment related loosely to the heat decay of the waste as well as to the toxicity of the waste in comparison to the original uranium from which the waste derives. Other regulatory periods have been suggested, such as 1,000,000 years or the time at which an exposed population would receive the peak dose (NAS: 1995).

By the time the EA became final in 1986, the advantages of developing a repository at Yucca Mountain seemed only to have increased. Although the DOE scientists realized that significant uncertainties remained, they began to highlight the possibility of lateral diversion of water by the Paintbrush unit, that is, the "tin roof" that overlay the potential repository site (DOE: 1986, 6-137). In fact, lateral diversion coupled with an estimate of lower rainfall hitting the surface directly above the proposed repository led the DOE to conclude that Montazer's and Wilson's original prediction of 1 mm/yr may have been too high. "Although no firm value for moisture flux in the Topopah Spring unit has yet been established, all preliminary field and laboratory estimates *are less that 0.5 mm/yr*" (DOE: 1986, 6-151). Performance over 10,000 years, to be sure, cannot be improved over zero release. But the DOE was sufficiently encouraged by its preliminary assessments to claim the following (DOE: 1986, 6-295):

> … the [Nuclear Regulatory Commission] limits for the … release rate from the engineered barrier system can be met *without any engineered barriers other than the waste form* because the amount of water likely to be in contact with the waste is insufficient to cause higher rates of waste dissolution [emphasis added].

Refining the Predictions: 1988-1995

By 1988, a year after Congress had prevented the DOE from characterizing any site other than Yucca Mountain, the DOE's assessment of percolation flux dropped even further. Citing later work by Montazer *et al.* (1985) and Wilson (1985), the DOE scientists in Nevada maintained that "the percolation flux through the [Topopah Spring] unit…may well be about or much less than the 0.5 mm/yr predicted by Wilson" (DOE: 1988, 3-208). Thus, over a period of about five years, predictions of percolation flux fell by a factor of as much as 40—from Roseboom and Winograd's 4 mm/yr, to a DOE estimate of *as low as 0.1 mm/yr.*

Over the next seven years, the generally accepted mean value for percolation flux ranged from 0.02 to 1.0 mm/yr. In 1991, for example, DOE sponsored two performance assessments (PA). The PA's use complex mathematical models to predict the range of potential radionuclide releases from a repository. And of course the PA's are themselves dependent on the prediction of future percolation flux.[7] The first assessment used the values 0, 0.01, 0.05, 0.1, and 0.5 mm/yr for percolation flux. This analysis concluded that a repository would meet the 10,000 year standard set by the Environmental Protection Agency in 1985 (but remanded by federal appeals court order in 1987[8]), as well as the regulations developed by the Nuclear Regulatory Commission (NRC) (PNL: 1992). The second assesment used a distribution of values for percolation flux – ranging from 0 to 39 mm/yr with a mean of 1.0 mm/yr – and a "weeps" model that allowed for the independent flow of water through random and discrete fractures, rather than simply through pore spaces. This analysis concluded that, under some scenarios, the remanded EPA standard probably could not be met at Yucca Mountain (Sandia National Laboratory: 1992).

Two years later, the DOE sponsored another pair of PA's. In the assessment performed by Sandia National Laboratory (1994), percolation flux ranged from 0 to 7 mm/yr. In the assessment performed by TRW (1993)—the management and operating contractor for Yucca Mountain—percolation flux ranged from 0 to 3 mm/yr (Van Luik, 1994). Those ranges were based on informal expert judgment that, in turn, rested on the limited experimental data that were available at the time. The mean value for percolation flux presumed in both studies was relatively low: 0.5 mm/yr, or eight times less than the Roseboom estimate. Once again, both sets of predictions showed that release of radionuclides to the accessible environment was strongly dependent on percolation flux. Perhaps more surprising was the conclusion of one assessment that if percolation flux were much above 0.1 mm/yr, long-term releases (post-100,000 years) would exceed the remanded EPA standard by as much as an order of magnitude (TRW: 1993).

Similar findings were obtained from a third set of performance assessments two years later (TRW: 1995). Yet by then, thinking about percolation flux had almost achieved the status of conventional wisdom. For example, although cautioning against accepting the DOE's estimates of percolation flux uncritically, the independent U. S. Nuclear Waste Technical Review Board (NWTRB; the Board) observed: "If it can be shown definitively that the percolation flux at the repository horizon is primarily matrix flow, less than 0.1 mm/yr, then it probably will be difficult not to deem the site 'suitable' on hydrologic grounds" (NWTRB: 1996, 28).

Observing Percolation Flux: 1996 to 1999

Until 1995, predictions of percolation flux were derived from indirect measures using data obtained from corings and supplemented by the results of computer simulations. In generating these predictions, scientists had to make assumptions, many of which of course seemed plausible at the time. One key assumption was that water flowed mainly in the matrix, or pore spaces, of the rock; another was that lateral diversion by the tin roof formed by the Paintbrush tuff formation was generally effective. For the most part, neither assumption came under direct challenge, although Flint's work on infiltration (1995) suggested that lateral diversion would have to be *extremely* effective to limit percolation flux to approximately 0.2 mm/yr.

By 1996, however, the Exploratory Studies Facility (ESF), a five-mile tunnel that parallels the eastern boundary of the potential repository emplacement area, offered a new opportunity to obtain rock samples from deep within the UZ. What was discovered took the Yucca Mountain project personnel by surprise.

Scientists at Los Alamos National Laboratory began systematic sampling every 200 meters within the ESF, as well as sampling in or adjacent to faults and concentrations of fractures. Analyzing these specimens in June 1996, they discovered that some contained significantly elevated levels of chlorine 36 (^{36}Cl). This radioisotope can occur naturally, but most ^{36}Cl was created and entered the atmosphere as a result of the above-ground nuclear weapons tests that took place before 1963. Thus, the presence of ^{36}Cl strongly suggests that water can move nearly 300 meters from the top of Yucca Mountain to the nominal repository horizon in less than 50 years. The presumption that water might flow so far down via *fast paths* was strengthened because most of the samples containing elevated ^{36}Cl levels were collected near faults and fractures that appeared to extend from the ESF tunnel to the surface of Yucca Mountain.

Strictly speaking, the ^{36}Cl discovery only provided direct evidence that the groundwater travel time, i.e., the time it took water to move down approximately 300 meters from the surface of Yucca Mountain to the repository horizon, was much faster than previously anticipated. It did not say anything about the volume of water moving through the fractures. Nonetheless, the findings by Los Alamos led the DOE to revisit its fundamental assumptions about how much water flows in fractures versus how much flows through the rock matrix in the UZ. By October 1996, the DOE reviewed saturation and moisture tension data, pneumatic data, fracture coating data, temperature data, and perched water data through a distinctly different lens. Out of that review came a strikingly different conceptual model of flow in the UZ (Williams and Bodvarsson: 1996).

The NWTRB summarized the changed thinking stimulated by the discovery of ^{36}Cl at the repository horizon. The Board first addressed the question of water distribution. The new data strongly suggested that two distinct flow systems coexist at Yucca Mountain. In one flow system, the water travels rapidly through interconnected fractures. Moreover, the amount of water present must be sufficient to allow gravity--which pulls the water downward toward the repository--to overcome the capillary action that tends to "suck" water out of the fractures and into the porous matrix of the rock. These conditions could be met—and the "fast paths" activated—episodically, by infrequent, intense precipitation events. In the other flow system, the water travels continuously through interconnected pores in the rock, and may take as long as 30,000 years to reach the repository level, compared to the 50 years or less indicated by the ^{36}Cl. The Board then considered the question of lateral diversion and concluded that the "tin roof" of the Paintbrush was, at best, leaky (NWTRB: 1997, 13-14). Nonetheless, the critical question of *how much water* flowed in each system remained unanswered.

Over the next year, the DOE tried to integrate the implications of the ^{36}Cl findings into its thinking. Unable to mount experiments to improve its predictions about percolation flux, the project formally elicited the views of seven experts. After reviewing the available data, an independent facilitator intensively probed the opinions of each of these scientists. Based on that interrogation, each individual expert developed his own distribution of what the average percolation flux at the repository horizon might be. The distributions of these seven opinions were combined to produce an aggregate distribution that had a mean of approximately 10 mm/yr and a 5th to 95th percentile range of 1 to 30 mm/yr (UZFM: 1997). In short, rather than being protected by a tin roof, a repository at Yucca Mountain would likely sit under something more akin to a torn wet blanket.

Why Did Predictions of Percolation Flux Change?

In 1983, Roseboom, with the help of Winograd, suggested that percolation flux at Yucca Mountain was roughly 4 mm/yr. Fourteen years later, a panel of experts convened by the DOE came up with an estimate that was about a factor of two higher. Yet, for most of the period stretching from 1985 to 1996, scientists involved in the repository project held that percolation flux was as much as 100 times smaller. These oscillations are illustrated in Figure 10.2 below. In this section, I propose two

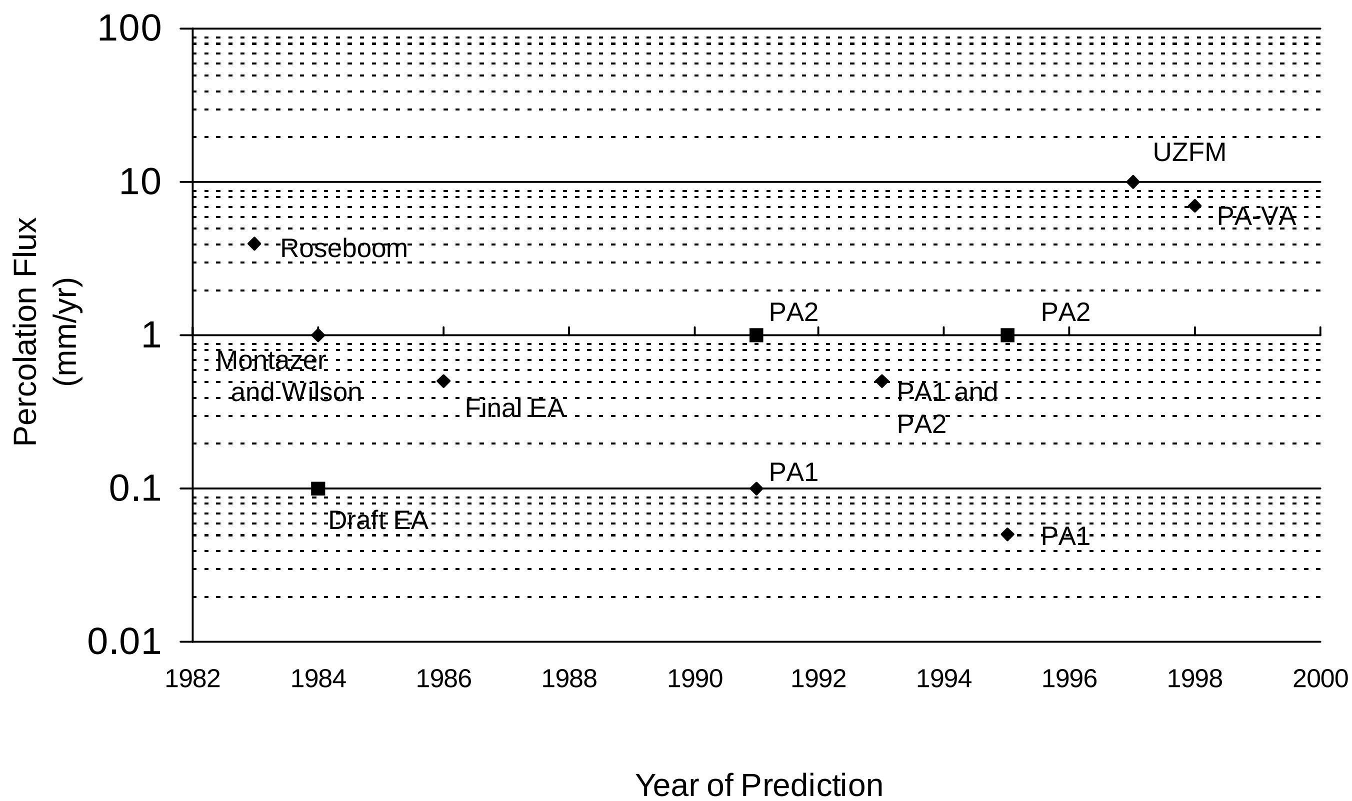

Percolation Flux
(mm/yr)
100
10
1
0.1
0.01
Roseboom
Montazer
and Wilson
Final EA
Draft EA
PA2
PA1
PA1 and
PA2
PA2
PA1
UZFM
PA-VA
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
Year of Prediction

Figure 10-2

complementary explanations of why estimates of percolation flux remained so low for so long.

I should note at the start that although "explaining" organizational behavior is more an art than a science, the effort is informed by persuasive theoretical constructs and an expanding volume of empirical research. Nonetheless, definitive answers are almost impossible to establish; generally the best that one can do is to suggest explanations that are plausible and consistent with a large number of known facts and actions.

Given this caveat, the first, and the most straightforward, possible explanation is that geologists associated with the project did they best they could in developing the predictions, given the limits on obtaining relevant data and the state of the science. The calculations, completed during the mid-1980's, relied on indirect methods (Montazer and Wilson: 1984; Wilson: 1985), limited data, or computer simulations (Sinnock *et al.*: 1986). Only after direct access was gained to the Topopah Springs unit through the ESF tunnel could scientists easily obtain samples that would speak more directly to the question of percolation flux. Without that data, the prediction of low percolation flux did not seem unreasonable. Nevertheless, it appears as if the predictions did underestimate the value of the percolation flux.

A second possible explanation recognizes that a variety of psychological, bureaucratic, political, economic, and regulatory influences, at various times, could have affected predictions made by project scientists and managers. By suggesting that these institutional forces also might have been at work, I am not claiming that the technical analysts were biased or unprofessional. My position is much more nuanced: I believe that those institutional forces all moved in the same direction. Consequently, when faced with the need to resolve uncertainty about percolation flux, the scientists had little organizational incentive to settle on a higher value or, more important, to question whether a lower value was correct. This approach to addressing uncertainty need not have been adopted consciously; in fact, it probably was not. More likely, it arose simply because organizational norms and culture have a well-documented and pervasive effect on individuals' actions and judgments (Steinbrunner: 1974).

Managing uncertainty by reducing the size of the estimated percolation flux was not scientifically unreasonable and probably offered the path of least resistance to bureaucratic momentum, especially early on, when it appeared that performance was not very sensitive to the magnitude of the flux (Thompson *et al*.: 1984; Sinnock *et al*.: 1984). Later, however, institutional pressures probably became less subtle. For that reason, considering separately what took place before 1988 and what happened afterward is useful.

Running a Horse Race**.** Before 1988, site-characterization work was parceled throughout the DOE complex. Three contractor organizations had the responsibility for conducting the technical analyses of the nine sites initially selected by the DOE. Rockwell International studied basalt at Hanford, Washington, and reported to the DOE's nearby Richland Operations Office. Battelle Memorial Institute investigated salt at seven locations stretching from Utah to Mississippi and reported to the DOE's Chicago Operations Office. SAIC was a major contributor to the work at Yucca Mountain and reported to the DOE's Nevada Operations Office.

These contractors offered their services to the government for profit; whoever survived the winnowing process from nine to five to three candidate repository sites would receive a steady stream of funds for perhaps as long as 10 years. By the same token, the scientists working for each contractor understood that their future jobs depended on their making a persuasive case that "their" site could perform well. Finally, because the contractor associated with the site that was selected for repository development would secure a federal commitment for many more years, each DOE Operations Office also had a programmatic and bureaucratic stake in the outcome of the horse race, albeit to a somewhat lesser degree than the contractor firms and their employees. Beyond these rather pragmatic considerations, scientists and managers at each site realized that helping to develop the country's first high-level radioactive waste repository would be a significant professional and personal accomplishment.

Jockeying for position began in 1983 as the DOE's headquarters staff started to put together drafts of the site-suitability guidelines (10 CFR 960), the criteria by which the three finalists and the winner of the horse race would be judged. Each DOE Operations Office, aided by its associated contractor corps, filed comments, many of which were designed either to remove language that placed its site at a disadvantage or to include language that gave its site a boost. These efforts intensified in 1984 as the guidelines were close to being published. For example, Jeffrey Neff, head of the Salt Repository Project Office in Chicago and responsible for overseeing characterization of a salt site in rural Utah, sought to remove language limiting the transportation of waste through a National Forest (Neff: 1984). Stephan Whitfield of the Richland Operations

Office expressed concern about a disqualifier having to do with groundwater travel time, which, if accepted as then written, would have hurt Hanford's chances (Whitfield: 1984). On the other hand, Donald Vieth, Director of the Waste Management Project Office in Nevada, strongly supported the wording of the criteria for groundwater travel time, believing that water moved very slowly in the unsaturated zone at Yucca Mountain (Vieth: 1984).

Finalizing the guidelines did not end the competition but only intensified it. The philosophy of looking at diverse geologic repository settings had been established years earlier by the Interagency Review Group on Nuclear Waste Management (IRG: 1978), and was incorporated both into the NWPA and the Nuclear Regulatory Commission's licensing regulations. Given this philosophy, insiders generally expected that one of the salt sites, the Hanford basalt site, and the Yucca Mountain tuff site would be the three finalists. But nothing could be taken for granted. Investigators at Hanford had to overcome the seemingly persuasive technical argument that fractures in basalt would almost be impossible to model. Scientists at Yucca Mountain had to present a compelling case that disposal in the UZ made as much sense as disposal in the SZ. In addition, the DOE had an organizational and budgetary incentive to keep the competition going among the final three sites (U.S. Senate: 1987, 167). Neff expressed a high level of confidence in the suitability of the Deaf Smith, Texas salt site (U.S. Senate: 1987, 166). Nonetheless, the confidence expressed by Vieth about the prospects for Yucca Mountain is especially striking (U.S. Senate: 1987, 71):

> We have looked at the site fairly thoroughly since 1977. I think we understand the nature of the forces that are acting on the site. If one takes the information we have now, and tries to project the kinds of things that are liable to be discovered in the next five or six years of site characterization, *it is not conceivable to me that we would discover something of a major nature that would cause us to change our mind about it*…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.* I think that we are very confident about the potential of that piece of earth to isolate the waste if it is placed there. [emphases added]

Vieth's confidence flowed from the reasoning in the final EA, published barely a year earlier (DOE: 1986). In that document, the Yucca Mountain scientists developed an implicit waste isolation strategy that appeared just as technically elegant as the one that had been advanced for salt. If very little water contacts the waste, then even relatively thin waste packages will take a long time to corrode. If the packages are corroded, there will be little water for dissolving the waste. And if the waste is dissolved, there will be little water for transporting the waste out of the repository. Moreover, because groundwater travel time through the UZ below the repository horizon was thought to be very long, the waste would take thousands of years to travel to the accessible environment. Finally, a dry repository also might be cheaper. Robust waste packages that resist corrosion might not have to be purchased.

To clinch the argument, the Yucca Mountain scientists reminded everyone that other means of isolating and containing the waste were being held in reserve, to be marshaled if needed to improve repository performance (DOE: 1986, 2-296). Heat from the waste packages would dry out nearby rocks, thereby reducing even further the amount of water seeping into the drifts. Moreover, between the Topopah Springs unit, where the repository would be located, and the water table below, lay a unit of absorptive volcanic sediments that would act as a sponge and further retard the migration of radionuclides to the accessible environment.

One anonymous reviewer of this chapter asked whether political considerations, such as the fact that Yucca Mountain is located in a sparsely populated and relatively politically weak state, might have engendered these relatively optimistic conclusions. Although members of Congress sought to enact legislation that would "disqualify" sites in their constituencies while the "horse-race" was unfolding, I believe that far stronger internal bureaucratic influences sought to demonstrate the suitability of various sites, thereby keeping them in contention. And in this context, the key to waste isolation at Yucca Mountain remained percolation flux. Notwithstanding analyses that suggested repository performance was insensitive to the magnitude of the percolation flux (Thompson et al., 1984; Sinnock et al., 1984), it would be much easier to demonstrate that a repository would perform satisfactorily if a case could be made that the repository horizon was dry to begin with.

Crossing the Finish Line. The 1987 amendments to the NWPA made the Yucca Mountain team the presumptive winner not only of the horse race to become a finalist but also of the contest to become the repository. Yet, there was the matter of crossing the finish line. The newly created independent Nuclear Waste Technical Review Board, made up of distinguished scientists, would have to validate the DOE's technical work, and the Nuclear Regulatory Commission would have to grant a repository construction license using an adjudicatory and potentially very adversarial process.

Complicating matters further, the project found itself caught up in a large number of political, bureaucratic, economic, legal, and regulatory controversies and debates between 1990 and 1993. Officials from Nevada launched an intensive legal, technical, and administrative campaign against the selection of Yucca Mountain. Coordination between the DOE headquarters and the Nevada Operations Office began to break down; by 1991, the project director was operating relatively autonomously. Site-characterization costs seemed to be mounting at a rate that was not sustainable much further into the future. As that effort experienced serious delays in schedule, utilities that owned reactors began to complain that the DOE would not meet its contractual obligation to begin accepting spent nuclear fuel on January 31, 1998. Industry representatives and state public utility commissions started filing law suits to protect the money collected from nuclear power consumers that was intended to pay the costs of disposal. So turbulent was the environment facing the Yucca Mountain project that Senators Pete V. Domenici and J. Bennett Johnston, two of the most influential lawmakers on energy policy, suggested, apparently out of frustration, that Congress terminate the effort altogether (U.S. Senate: 1992, 34-40).

By early 1995, the Yucca Mountain project was virtually under siege. Calls for its termination increased. In the view of the project's critics, too much money was being spent, too little progress had been made, and the prospects for final regulatory approval were too problematic. Although the program ultimately survived because the need for a repository remained, Congress cut the project's budget request by 50 percent, and more than 1,000 contractor employees were laid off. These events led many people to believe that the very idea of developing a repository within the next 50 years was hanging in the balance. One of the most articulate proponents of that view was the Director of DOE's Office of Civilian Radioactive Waste Management, Daniel Dreyfus. Speaking to the NWTRB in October 1995, Dreyfus observed:

> The issue confronting us is whether the program can sustain meaningful progress towards a future decision on geologic disposal with a funding level that is significantly below that which was required for our current program approach. We inside the program gave serious consideration to this question, and we believe, albeit tentatively, that it can. We must, however, convince the Congress that continued pursuit of geologic disposal is, first of all, worth at least $250 million a year, and second of all, that it will have meaningful results. To do this, we have to ensure that scientific investigation can *produce results within a reasonable time frame*… [emphasis added; Dreyfus: 1996].

Over the next year, the urgency of producing demonstrable results dominated the public pronouncements of the OCRWM's senior and mid-level managers and, perhaps more important, the ongoing dialogue that took place inside the program. Speaking bluntly before the National Academy of Science's Board on Radioactive Waste Management, Dreyfus strongly linked the outcome of his vehicle for showing progress– the so-called viability assessment (VA) – to the future of geologic disposal over the next several generations. Although this same theme had been sounded in an earlier talk to the NWTRB, it had been more muted then. The VA, which was subsequently mandated by Congress, would develop a preliminary waste package and repository design, a safety analysis, a compilation of key research issues that would be addressed prior to site licensing, and a cost estimate for operating and closing the repository. Now, Dreyfus sent an explicit signal to supporters of geologic disposal that although the technical precision of the VA might not overwhelm them, they had better be prepared to give the assessment at least qualified support. If they were not willing to do so, they might not like the consequences—elimination of the geologic disposal option—and they would have only themselves to blame.

These external threats to the Yucca Mountain project were emerging and spreading just as the DOE's performance assessments were showing problematic repository performance if percolation flux rose appreciably above 0.5 mm/yr. No wonder, then, that the first formal version of a waste containment and isolation strategy released in July 1996 relied almost entirely on the existence of a dry repository (DOE: 1996). Any other view would have opened the door to a new round of intense criticism.

Thus, the predictions of low percolation flux that scientists converged on between 1984 and 1995 had become almost an article of faith upon which the future of the project now rested.

Outcomes and Implications

How are scientific activities carried out in a large public bureaucracy that operates in a very turbulent social and political environment?

In the so-called "realism" school of the philosophy and sociology of science, scholars recognize that scientific activities do not generate absolute or final "truth." Instead, those investigators understand that scientific activities can produce contingent knowledge that is always subject to recall. In their view, science is an *error-correcting* activity in which new information continually challenges accepted wisdom; over time, knowledge accretes.[9]

What happened at Yucca Mountain is consistent with this perspective. The DOE *did* modify its predictions after data were obtained calling into question the low estimates of percolation flux. In fact, it even issued a press release notifying the public about the Los Alamos ^{36}Cl findings. The credit for these actions, in the first instance, belongs to the scientists and managers of the DOE. They were willing to put their "faith" to a test by sponsoring the Los Alamos research; they also resisted the urge to reinterpret or explain away the unexpected findings. This does not mean that the implications of the Los Alamos work on ^{36}Cl were universally or gracefully accepted within the project, either then or now. In fact, there was considerable internal debate over how much significance should be attached to those findings. For example, the project commissioned an external peer review to examine whether the methodology used by Los Alamos was appropriate. That review generally supported the research. Even so, in January 1999, the DOE began a validation study of bomb-pulse ^{36}Cl occurrences in the ESF test tunnel.

Nonetheless, steps were taken almost immediately to incorporate a higher percolation flux in key project activities. The formal expert elicitation was launched (UZFM: 1997); a revised waste containment and isolation strategy was published (DOE: 1998a); and the evaluation of repository performance being conducted as part of the VA was redirected (DOE: 1998b). In the areas of repository and waste package design, however, the project did experience significant difficulties in integrating the information that Yucca Mountain might be wetter than previously thought. As a result, the designs contained in the VA had to be revised (DOE: 1998c; TRW: 1999).

Technical experts familiar with attempts to predict percolation flux seem convinced that the current, higher, estimates for that parameter are much more valid than predictions made at the beginning of 1996. But are these predictions “right”? Even scientific realists would be reluctant to claim more than that knowledge is accreting along a jagged path that approaches, but does not necessarily reach, a “correct” answer. Thus, it is still unclear today what that “correct” answer is.

To reduce further the uncertainty in percolation flux, the NWTRB urged DOE to excavate a new drift across the proposed repository block, more or less perpendicular to the ESF tunnel (NWTRB: 1997, 26). This so-called “east-west crossing” would enable the DOE, among other things, to gather additional information about the distribution of fractures at the repository horizon. Chairing a review of the VA for the Director of the USGS, Isaac Winograd, the father of disposal of waste in the UZ at Yucca Mountain, detailed why having this better information could be important (Winograd *et al.*: 1998, 10):

> It is our view that the [viability assessment] overestimates percolation [fluxes] at the repository horizon and overestimates seepage into the emplacement drifts by an even wider margin. Consequent to these over-estimations are various proposed engineering measures to protect against the deleterious effects of seepage. We believe that some of these engineering measures may be unnecessary and others counterproductive with respect to the natural assets of the repository system.

But, in the final analysis, how much information is enough and how good predictions need to be is a policy judgment. Exercising its discretion, the DOE initially refused to commit to when they would construct the east-west crossing; under pressure from the NWTRB, the DOE eventually excavated this drift in 1997. As of mid-1999, however, very few experiments had been carried out in the new drift. For example, although scientists from Los Alamos collected samples in the east-west crossing to detect the presence of ^{36}Cl, many of those specimens have not been analyzed. Preliminary results indicate that bomb-pulse ^{36}Cl has been found along two known faults and at two of three previously unidentified faults in the east-west crossing. At one of these previously unidentified faults, the bomb-pulse signal was the strongest yet measured at the site. But samples taken between faults have not been analyzed. This work, therefore, probably will not be able to reduce the uncertainty in predicting the contribution of fast flow paths to the overall percolation flux. Thus, it is unclear at this time how much better information the DOE will have about percolation flux at Yucca Mountain when it decides on the site's suitability in mid-2001.

Can institutions be designed to increase the validity of technical undertakings?

Starting with the earliest efforts to site a high-level waste repository by the DOE's predecessor agency, the Atomic Energy Commission, concerns have been raised about whether political considerations would overwhelm the agency's technical assessments (Carter: 1987, SEAB: 1993). Consequently, the law creating the DOE required that an independent agency, the Nuclear Regulatory Commission, license a high-level waste repository. The events noted above leading to the passage of the NWPA Amendments, however, reinforced the concerns of many policy-makers about the program's credibility. The Nuclear Waste Technical Review Board was established to ensure that DOE's decisions are technically valid (U.S. House of Representatives: 1987).

According to some theories about organizational design, the involvement of two independent technical monitors—the NRC and the NWTRB—ought to have increased the likelihood of discovering in less than a dozen years the DOE's likely underestimation of percolation flux (Landau: 1969). But reality is more complicated. None of the monitors had any data other than what was available to the DOE. For example, commenting on the 1986 EA, the NRC noted (1986, 46):

> The choice in the draft EA of a value of [percolation flux equal to 1 mm/yr] …was considered to be inadequately supported and the suggestion

> was made that higher values be considered [by the DOE]. In the final EA, this value has been *reduced* to a constant value of 0.5 mm/yr…The NRC staff concludes that the values of flux have not been adequately considered in [the DOE's] analysis.

But the NRC had no scientific basis for going a step further and asserting that the DOE made a predictive error. Moreover, although the NWTRB urged the DOE to construct the ESF tunnel, in part so that better percolation flux data could be gathered, it was not until 1995 that the Board systematically examined the DOE's low predictions of percolation flux. Perhaps one could argue that both monitors fell down on the job. But, given the dearth of data and the underlying uncertainty in the models—which made it impossible to arrive at definitive conclusions—those arguments strike me as products of 20/20 hindsight.

Moreover, other institutional arrangements probably facilitated the DOE's own acknowledgment that its earlier predictions of percolation flux might not be correct. First, all data were gathered under a quality control regime. The data then were made available to the public. Second, the project's technical overseers recognized and carefully evaluated implications of the new data for repository performance. For example, the NWTRB continually pointed out to DOE that its proposed repository design might not be compatible with a "wetter" Yucca Mountain. Third, DOE officials knew they might ultimately have to defend their technical positions before an NRC licensing board in an adjudicatory process. The State of Nevada is on record that it will intervene in that process and contest the DOE's application for a permit. This likely intervention forces the DOE into substantiating and documenting its predictions. Thus, taken together, a variety of mechanisms designed to safeguard the scientific process appear to have worked.

I would conjecture that at least some of these mechanisms were especially effective because the DOE's senior managers came to realize that the Yucca Mountain project was not immediately threatened by the finding that the percolation flux was considerably higher than predicted. To be sure, it took the organization a while to coalesce around a new vision of how a repository at a "wetter" site might function, but ultimately it did so. On the surface, this vision does not appear much different from the earlier ones. Its major attributes – limited water contacting waste packages, long waste-package lifetimes, slow rates of radionuclide release, and reduction in concentration of radionuclides during transport – are similar, if not identical, to the attributes of the old concept of how a repository is likely to perform.

What is strikingly different, however, is how performance is now allocated between the natural and the engineered components of the repository system. Results from the latest performance assessment sponsored by the DOE were published as part of the VA (DOE: 1998b). For the first 5,000 years, average percolation fluxes assumed in the assesment ranged from about 4 mm/yr to about 11 mm/yr. As a result, for the first 10,000 years, the expected value of releases to the accessible environment was projected to be at least two orders of magnitude lower than the remanded EPA standard. This low dose derives from the expected behavior of the spent fuel cladding, which holds the fuel pellets in the fuel rods, and the expected robustness of the then-current reference design of the waste package, which consists of two shells. The outer shell is made of carbon steel; the inner shell is a relatively new nickel alloy, C-22, that appears to have very high corrosion resistance. Using mathematical models, the DOE has made predictions about how the cladding and waste package would degrade over time. Those models, however, critically depend on what are in essence two assumptions: the integrity of the cladding after the spent fuel has been removed from the reactor and the corrosion rate for C-22. The VA indicates that even after 100,000 years, these waste packages will maintain sufficient integrity that the predicted value of the release would be approximately 20 percent of the remanded EPA standard. Only after 150,000 years, as the waste packages begin to fail in greater numbers, would radionuclide release to the accessible environment begin to exceed that limit; it then would continue to rise for another 150,000 years, when the dose would be roughly an order of magnitude higher than permissible under the remanded EPA standard. DOE is examining various engineering enhancements to reduce these projected doses further.

How helpful are geologic predictions in developing public policy?

It would seem that the original vision of a repository built at Yucca Mountain has been revised significantly: In 1986, no engineered barriers appeared to be needed because the percolation flux seemed so low. Because the flux was underestimated, both as a result of the perils of predicting with little observational data and as a result of the subtle influence of many institutional forces, engineered barriers now may be indispensable.[10]

I use the word "may" intentionally. The natural barriers associated with Yucca Mountain, such as retardation in the UZ and dilution and dispersion in the SZ, could very well be more effective than the latest performance assessment holds them to be. The dilemma for the DOE is that this effectiveness may be quite difficult to demonstrate because of the complexity of the geology at and around Yucca Mountain. For example, modeling the flow of radionuclides in the SZ has proven more difficult than earlier anticipated. So, at the moment, at least, the DOE finds itself in the awkward position of promoting a geologic repository whose performance appears to depend more on the robustness of the waste package and other engineered elements than on the attributes of the natural system such as the geology and the hydrology of the site.

There may be other outcomes and implications that have not yet fully manifested themselves; only the passage of time will clearly reveal them. Some probably will be relevant to policy-makers because they arise from a vision of geologic disposal that has changed substantially over the last 15 years (although it is consistent with the views set out by the IRG in 1978). Others probably will bear on whether the DOE will be able to meet its policy objectives, which include protecting human health and the environment and preventing the export of significant risks to future generations. At least in the view of DOE leaders, fulfilling those objectives requires that Yucca Mountain receive a construction license by the year 2010. Will DOE scientists be able to demonstrate convincingly the protective power of the engineered components in that time frame? Can a more technically defensible case be made that Yucca Mountain's natural elements of the repository system contribute significantly to waste containment? The answers to these questions, as we have seen, of course depend on science and engineering, but also on economics, project schedules, and political judgments.

Conclusions

More than a century ago, the German sociologist Max Weber suggested the value of the organizational form known as a "bureaucracy." Such organizations exercise power legitimately because they can bring knowledge to bear to solve problems. Too often, however, members of the general public and policy-makers hold strong negative images about bureaucracies, especially public ones. Bureaucracies are perceived to be inflexible, inefficient, and, most important, incapable of learning (Crozier: 1964). This essay should reinforce other works that illuminate modern bureaucracies using a more variegated light. In particular, I believe that the following lessons can be drawn from this case.

- *Notwithstanding institutional pressures that appeared to lower estimates of percolation flux, when relevant new data were acquired, those estimates were revised.* The scientific process, as understood by the realist school, seems to be working. I suspect that the dramatic and relatively unambiguous nature of the ^{36}Cl data facilitated the process of revising predictions of percolation flux. In advancing this cautiously positive conclusion, I realize that the process has not been entirely smooth. The DOE has exercised its discretion in determining the resources and schedule for gathering new information about percolation flux. That judgment has not always been supported by those responsible for project oversight.

- *Independent technical reviewers often can help detect predictive mistakes, but their utility may be less than many organization theorists assert.* Not only did the absence of meaningful data make the DOE's job of predicting percolation flux more difficult, but it also hindered the efforts of the two independent technical overseers, the NRC and the NWTRB. Complicating matters further, just because attention is called to the existence of technical errors does not automatically mean that they will be corrected. The NRC, for example, possesses the authority to license a repository, but it is often reluctant to intervene on particular technical issues long before a license application is submitted. The NWTRB, in contrast, has no regulatory authority. Its stature as a independent, Presidentially appointed body may or may not be sufficient reason for the DOE to accept its recommendations.
- *A variety of institutional mechanisms can be effective in increasing the likelihood that the strengths and weaknesses of geologic predictions will be subjected to technical and public scrutiny.* Senior managers can facilitate organizational learning by creating a supportive culture and environment. In the case of federal agencies, Congress and the Office of the President can establish processes that also facilitate accountability in the predictive effort. For example, the NRC's current plan to hold an adjudicatory licensing hearing on Yucca Mountain has forced the DOE to be much more careful in documenting and establishing its scientific and technical positions.

- *Senior managers who diversify their technical approaches to a problem (multiple designs, defense-in-depth, a systems perspective rather than an individual-component perspective) may be better positioned to alter courses if required.* To expect organizational leaders to engage figuratively in bureaucratic *hara-kiri* may not be reasonable. The higher the potential stakes involved in modifying predictions, the more difficult the process may be. If key leaders in technically based organizations can identify alternative paths to securing desired policy objectives, the chances of acknowledging predictive mistakes increase. For example, because engineered containment was seen as a possible option, the DOE may have more readily accepted the implications of the ^{36}Cl studies.

Disposal of radioactive waste has been on the public agenda for more than 40 years. Within the next decade, the Yucca Mountain project probably either will have “crossed the finish line” or will have “faltered down the stretch.” I believe, however, that the lessons of this chapter on DOE’s scientific work at Yucca Mountain do offer some hope that within the next generation a start can be made in dealing with one of the most significant environmental issues confronting the United States.

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References

American Physical Society (1978). "Report to the American Physical Society by the Study Group on Nuclear Fuel Cycles and Waste Management," *Report of Modern Physics*, 50, January, 1978.

Carter, L. (1987). *Nuclear Imperatives and Public Trust: Dealing with Radioactive Waste*, Washington, DC, Resources for the Future.

Colglazier, E.W. and R.B. Langum (1988). "Policy Conflicts in the Process for Siting Nuclear Waste Repositories," *Annual Review of Energy*, 13, 317-357.

Crozier, M. (1964). *The Bureaucratic Phenomenon*, University of Chicago Press.

Department of Energy (1981). *Final Environmental Impact Statement on the Management of Commercially Generated Radioactive Waste*.

--------- (1984). *Draft Environmental Assessment, Yucca Mountain Site, Nevada Research and Development Area*, DOE/RW-0012.

--------- (1986). *Environmental Assessment, Yucca Mountain Site, Nevada Research and Development Area*, DOE/RW-0073

--------- (1988). *Site Characterization Plan, Yucca Mountain Site*, DOE/RW-0199.

--------- (1996). *Repository Safety Strategy: U.S. Department of Energy's Strategy to Protect Public Health and Safety After Closure of Yucca Mountain*, Rev. 0, YMP/96-01.

--------- (1998a). *Repository Safety Strategy: U.S. Department of Energy's Strategy to Protect Public Health and Safety After Closure of Yucca Mountain*, Rev. 2, YMP/96-01.

--------- (1998b). *Viability Assessment of a Repository at Yucca Mountain: Total System Performance Assessment*, DOE/RW-508.

--------- (1998c). *Viability Assessment of a Repository at Yucca Mountain: Preliminary Design Concept for the Repository and Waste Package*, DOE/RW-0508.

Dreyfus, D. (1996). Presentation to the Nuclear Waste Technical Review Board, October 17, 1995.

Flint A. (1995). "Shallow Infiltration Processes at Yucca Mountain, Nevada: Neutron Logging Data 1984-1993," USGS-WRI -95-4035.

Interagency Review Group (1978). *Subgroup Report on Alternative Technology Strategies for the Isolation of Nuclear Wastes*, TIS-28818 (draft).

Johnstone, J.K., R.R. Peters, and P.F. Gnirk (1984). "Unit Evaluation of Yucca Mountain, Nevada Test Site: Summary Report and Recommendation," SAND-83-0372.

Landau, M. (1969). "Redundancy, Rationality, and the Problem of Duplication and Overlap," *Public Administration Review*, 29, 350-357.

Montazer P. and W. Wilson (1984). "Conceptual Hydrogeologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada," USGS-WRI-84-4345.

Montazer P., E.P. Weeks, F. Thamir, S.N. Yard, P.B. Hofrichter (1985). "Monitoring the Vadose Zone in Fractured Tuff, Yucca Mountain, Nevada," in *Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone, November 19-21, 1985, Denver, CO*, National Water Well Association, pp. 439-469.

National Academy of Sciences (1957). "Disposal of Radioactive Waste on Land," Washington, DC.

National Academy of Sciences (1995). *The Technical Basis for the Yucca Mountain Standard*, Washington, DC, National Academy Press.

Neff, J. (1984). Memorandum to B. Hewitt, April 16,1984.

Nuclear Regulatory Commission (1986). "NRC Staff Comments on the DOE Final Environmental Assessments," Division of Waste Management, December 22, 1986.

Nuclear Waste Technical Review Board (1991). *Fourth Report to the US Congress and the US Secretary of Energy*, Arlington, VA.

--------- (1996). *Report to the US Congress and the US Secretary of Energy*, Arlington, VA.

--------- (1997). *Report to the US Congress and the US Secretary of Energy*, Arlington, VA.

--------- (1998). *1997 Findings and Recommendations*, Arlington, VA.

Office of Technology Assessment (OTA) (1985) *Managing the Nation's Commercial High-Level Radioactive Waste*, Washington, DC.

Pacific Northwest Laboratory (1992). "Example of Post-Closure Risk Assessment Using the Potential Yucca Mountain Site," Richland, WA.

Robertson, J.B., G.L. Dixon, and W.E. Wilson (1982). Letter to M. Kunich, February 5, 1982.

Roseboom, E.H. Jr. (1983). "Disposal of High-Level Nuclear Waste Above the Water Table in Arid Regions," Geological Survey Circular 903.

Sandia National Laboratory (1992). "An Initial Total-System Performance Assessment for Yucca Mountain," SAND-91-2795.

-------- (1994). "Total-system Performance Assessment for Yucca Mountain - SNL Second Iteration," SAND-93-2675.

Secretary of Energy Advisory Board (1993). *Earning Public Trust and Confidence: Requisites for Managing Radioactive Wastes*, Washington, DC.

Sinnock, S., J.P. Brannen, Y.T. Lin (1984). "Preliminary Bounds on the Expected Postclosure Performance of the Yucca Mountain Repository Site, Southern Nevada," SAND-84-1492.

Sinnock, S., Y.T. Lin, and M.S. Tierney (1986). "Preliminary Estimates of Groundwater Travel Time and Radionuclide Transport at the Yucca Mountain Repository Site," SAND-85-2701.

Steinbrunner, J. (1974) *Cybernetic Theory of Decision-Making*, Princeton, NJ, Princeton University Press.

Taubes, G.(1993). *Bad Science: The Short Life and Hard Times of Cold Fusion*. New York: Random House.

Thompson, F.L., F.H. Dove, and K.M. Krupa (1984). "Preliminary Upper-Bound Consequence Analysis for a Waste Repository at Yucca Mountain, Nevada," SAND-7875.

TRW (1993). "Total Systems Performance Assessment – 1995: An Evaluation of the Potential Yucca Mountain Repository."

------ (1995). "Total Systems Performance Assessment – 1995: An Evaluation of the Potential Yucca Mountain Repository."

---------- (1999). *License Application Design Selection Report*.

U.S. Geological Survey (1978). "Geologic Disposal of High-Level Radioactive Wastes – Earth Sciences Perspectives," Geological Survey Circular 779.

U.S. House of Representatives (1987). "Report: Establishing a Nuclear Waste Policy Review Commission, An Office of the Nuclear Waste Negotiator, and For Other Purposes," 100th Congress, 1st Session, 100-425, Part 1, Committee on Interior and Insular Affairs, November 5, 1987.

U.S. Senate (1987). "Nuclear Waste Program," Hearing before the Committee on Energy and Natural Resources, 100th Congress, 1st Session, Part 4, June 29, 1987.

U.S. Senate (1992). "Department of Energy's Civilian Nuclear Waste Program," Hearing before the Committee on Energy and Natural Resources, 102nd Congress, 2nd Session, March 31, 1992.

Unsaturated Zone Flow Model (1997). UZFM Expert Elicitation Project, US Department of Energy.

Van Luik, A. (1994). Presentation to the Nuclear Waste Technical Review Board, January 12, 1994.

Vieth, D. (1984). Memorandum to C. Hanlon, W. Hewitt, and P. Gnirk, March 10, 1984.

Whitfield, S. (1994). Memorandum to E. S. Burton, March 14, 1984.

Williams, D. and B. Bodvarsson (1996). "Conceptual Model of Flow in the Unsaturated Zone: New Insights," Presentation to the Nuclear Waste Technical Review Board, October 9, 1996.

Wilson, W. (1985). Letter to D. Vieth, December 24, 1985.

Winograd, I., R.E. Anderson, T.C. Hanks, T.E. Reilly, and E.P. Weeks (1998). "Viability Assessment of a Repository at Yucca Mountain: A Report to the Director, U.S. Geological Survey, November 25, 1998.

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[1] The views expressed in this chapter do not necessarily represent the views of the U.S. Nuclear Waste Technical Review Board, a presidentially appointed independent federal agency charged by Congress with evaluating the scientific and technical validity of the U.S. Department of Energy's high-level radioactive waste disposal efforts.

[2]As used in this paper, the term "radioactive waste" means spent nuclear fuel from commercial, research, and defense production reactors as well as the solidified products of reprocessing such spent nuclear fuel. For a more formal definition, see 10 CFR 50 Appendix F.

[3] Yucca Mountain is in the desert, approximately 75 miles by air northwest of Las Vegas, Nevada. Part of the land that has been set aside for the potential repository lies on the Nevada Test Site (NTS), where hundreds of nuclear weapons tests were conducted.

[4]In 1998, the U.S. Environmental Protection Agency (EPA) certified that the Waste Isolation Pilot Plant (WIPP), a repository located in a salt formation in southeastern New Mexico, could begin to receive transuranic-contaminated (TRU) radioactive waste. The certification came 20 years after Congress authorized the construction of the facility. In March 1999, the first shipment of TRU waste arrived at WIPP for disposal.

[5]For a discussion of this history, see my "Radioactive Waste Management Policymaking," Appendix A in OTA: 1995; and Carter: 1987.

[6] A year earlier, Robertson et al, 1982, presented a rough estimate of 3-6 mm/yr.

[7] The 1991 analysis was primarily undertaken to gain experience with the methodology and was not viewed as being especially valid. In the discussion that follows, the performance assessment results are accepted at face value. But I recognize that their conclusions are strongly influenced by model assumptions and approximations.

[8] In the 1992 Energy Policy Act, Congress directed the EPA to develop new dose-based standards for Yucca Mountain by 1994. As of July 1999, the EPA still had not promulgated a new standard for high-level radioactive waste. This lack of a standard prompted the DOE to examine in its PA's several different periods of compliance.

[9] For example, see Taubes, 1993.

[10]Once again, neither explanation is designed to cast aspersions on project scientists.