GEOLOGICAL ISSUES IN SITING U.S. NUCLEAR FACILITIES

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Summary
Geological issues often have played a critical, or apparently critical, role in siting and operating decisions for civilian nuclear facilities in the U.S. The issues include seismic hazard in regions of high and low seismicity, volcanism, and groundwater flow. A frequently cited concern has been the uncertainty associated with a specific scientific conclusion or statement. The acceptable level of uncertainty often is determined by an unspecified mix of social and political factors, as well as by technical considerations. Examples of geological issues at nuclear facilities are discussed, emphasizing the scientific controversies, the efforts made to resolve the controversies, and the lessons learned.

Introduction
As a result of the civilian nuclear power program that began more than 40 years ago, many nuclear facilities have been sited in the United States. They include more than 100 nuclear power plants and several low-level radioactive waste disposal facilities. Extensive efforts are under way to site a high-level radioactive waste disposal facility (repository) at Yucca Mountain in the state of Nevada. These projects have resulted in the accumulation of an extraordinarily large and detailed geologic database that has been useful to many outside of the nuclear industry. These efforts, both successful and unsuccessful, have provided important insights into the role of geology, which often has played a critical or apparently critical role in siting and operating decisions. Some of these decisions have highlighted the interactions between scientific issues and political and social issues and the difficulty often faced in distinguishing between them. Geologic uncertainties and the highly interpretive nature of the science have made a particularly fertile ground for disputes between those in favor of and those opposed to the siting and operation of nuclear facilities.

Although we discuss both nuclear power plants and nuclear waste disposal facilities, the role of geology in these two types of facilities is different. Nuclear power plants are highly complex, relatively short-lived (40 years) facilities, requiring sophisticated control technologies, whose failure could result in the immediate release of large amounts of harmful radionuclides. The role of geology is to provide sufficiently stable locations so that these facilities can operate safely. Nuclear waste disposal facilities are typically simple, passive, long-lived (hundreds to thousands of years) facilities, whose failure could result in the slow release of radionuclides well into the future. Geology, besides providing a stable environment for the engineered components of the facility, can be part of the disposal facility itself and play a critical role in the containment and isolation of the nuclear waste.

Our approach is to present some specific examples of geological issues at different facilities in the United States and to draw lessons from the examples. In our discussion of nuclear power plants, we concentrate on seismic issues. Earthquakes have been particularly controversial because of the ability of fault rupture and vibratory ground motion (shaking) to threaten the sensitive pressurized systems in nuclear power plants. In our discussions of nuclear waste repositories, we cover a broader range of issues emphasizing hydrogeology because groundwater is the primary means by which nuclear waste packages can be breached and radioactive waste transported to the environment.

Choosing a good site
The purpose of the siting process is to pick a good site, and geology has an important role in determining how good any site is. The geological attributes of a "good" site include its ability to fulfill its assigned functions (stable environment and/or containment and isolation); ease of characterization (not too heterogeneous); ease of understanding (no need to rely on overly complex and uncertain models); and the absence of possible adverse disruptive factors, such as significant seismic or volcanic activity. No site is perfect, and trade-offs exist between these technical factors and between technical and nontechnical issues such, as the willingness of the local population to host the facility. Our discussion in this area focuses on two sites where serious technical concerns exist.

In the early 1980's, the U.S. government enacted legislation encouraging states to form compacts and provide regional disposal facilities for commercial low-level radioactive waste. Such waste typically consists of metal components, resins, rags, and protective clothing that have been exposed to radioactivity or contaminated with radioactive material. (The much more potent high-level waste discussed below consists of the spent fuel from nuclear power reactors and the byproducts of reprocessing the spent fuel.) According to a 1999 report of the U.S. General Accounting Office (GAO), almost 600 million dollars has been spent over the last 18 years on as yet unsuccessful efforts to site and develop 10 regional low-level waste disposal facilities. One such site, near the town of Martinsville, Illinois, was selected for detailed investigation in 1988. In 1992, the governor of Illinois appointed a Siting Commission to review the work done and provide its recommendations on the site. After 72 days of hearings, the Siting Commission found that the proposed Martinsville site is not the place to dispose of low-level radioactive waste. Although the site "could meet some of the statutory criteria with respect to the proposed design... it did not present a suitable geologic and hydrologic medium and it was not located so as to minimize radioactive releases into ground waters utilized as public water." According to the Siting Commission, "The underlying site geology and hydrology—how thick and tight is the Vandalia Till [a supposedly low-permeability feature that was supposed to protect local aquifers directly beneath the site] and how long contaminated water would take to travel through to the Martinsville public wells—was never adequately explained."

The theme of too much uncertainty is a common thread in almost all disputes involving geological issues at nuclear facilities. In fact, as discussed later, depending on their background and motivation, different groups have different definitions of what constitutes an acceptable level of uncertainty. In the case of Martinsville, one of the three members of the Siting Commission, a retired dean of engineering at the University of Illinois and a consultant on nuclear facilities, pointed out in a 1994 presentation to the U.S. Nuclear Waste Technical Review Board (NWTRB). "As an engineer, I live with uncertainties...and I'm used to this. But the uncertainties in this project were immense."

Particularly damning was the Siting Commission's conclusion that the site "...is entirely too small to provide an adequate buffer zone, given the hydrogeologic nature of the site. [and]...is virtually enveloped in water. The facility site itself has a nearby creek on one side and a stream bordering another...The [site] is upstream of the City [Martinsville]—precisely the wrong side of a populated area on which to locate a disposal facility." Proponents of the facility argued that the Siting Commission had gone beyond its mandate and had invoked its own criteria for the site and how much uncertainty was acceptable. According to the Siting Commission, the site was located where it was to obtain local approval—the municipality wanted the facility, but the regional government did not. In the end, some 60 million dollars had been spent on studies for a site that, at best, was marginally acceptable as the location of a low-level radioactive waste facility.

An interesting example of how developing geologic knowledge has changed perspectives on the suitability of a site is that of the Humboldt Bay nuclear power plant on the northwest coast of California. Commissioned in 1963, the nuclear power plant operated without incident until 1975, when ground motions associated with a nearby moderate earthquake slightly exceeded the original seismic design specifications, although without damage to the plant. The plant subsequently was shut down for refueling and possible seismic retrofitting. In the meantime, local geologists discovered that highly active faults within 1 km of the plant were closely connected to the Cascadia subduction zone, a major tectonic plate boundary. The operator decided not to restart the plant. Another offshore earthquake in 1994 gave rise to ground motions at the site that were even slightly larger than those envisioned in the retrofit design. Very recent studies have shown that the subduction zone fault ruptured during a truly great earthquake in 1700 associated with a devastating tsunami along the entire northern California-Oregon-Washington-British Columbia coast. The plant has now been partly dismantled. Spent fuel still remains in storage at the plant, however, and because the fuel practicably cannot be moved to a completely different locality, efforts are under way to ensure that it is stored safely on-site. The principal challenges are (1) to avoid future tsunami flooding, perhaps by moving to higher ground on the same property, and (2) to design a storage facility to withstand the shaking on the hanging wall of a major thrust fault that lies directly beneath the site, the kind of seismo-tectonic environment that the 1999 Taiwan earthquake and other recent earthquakes have demonstrated to be among the most vulnerable to very intense earthquake shaking.

In retrospect, it is easy to say that the Humboldt Bay site was a poor location for a nuclear power plant. But even had the local faults been recognized at the time of initial planning, the threat they posed would not have been evident. It would be many years before the seismic capability of the Cascadia subduction zone, the relationship of the local faults to the Cascadia subduction zone, and the nature of near-field strong ground shaking, particularly that associated with the hanging walls of thrust faults, would become clear. It is the authors' opinion that geologic and seismologic understandings of seismic hazards will continue to change and evolve in years to come, and that many existing nuclear facilities worldwide may have to undergo challenging safety reappraisals.

Developing a broad data base

Although consensus exists on many important theories, such as plate tectonics, geologists are not united in their support for many of the models used to explain different phenomena. In the siting of nuclear facilities, disagreements among geologists over which is the "correct" model often surface as important issues. Although some models may be tested, others often require observations or tests that last long periods of time. If the uncertainty is such that one of the reasonably plausible models could result in a high probability of unacceptable consequences, the project may be doomed. If, on the other hand, such consequences are very unlikely, or if the models are constrained by the database in such a manner that the consequences are relatively bounded, model uncertainty may not be that significant.

For nuclear power plants, a source of great uncertainty was the occurrence of a large (magnitude 7+) earthquake in Charleston, South Carolina, in 1886. Many nuclear power plants were sited under the assumption that such an earthquake could not occur elsewhere along the eastern seaboard of the United States. Repeated efforts to define the source of the earthquake resulted in a string of competing hypotheses whose lifetimes varied from months to years. This unresolved uncertainty caused some to question seismic safety at tens of operating nuclear power plants in the eastern United States. In the mid-1980's, emphasis shifted from finding the causative fault to finding other evidence of large earthquakes in the regions. A detailed evaluation of earthquake-induced liquefaction (sand blows) allowed the identification of five large, pre-1886 earthquakes that occurred in the Charleston region during the last several thousand of years. This study also showed that the number and size of the sand blows decreased with increasing distance from Charleston. Although this study did not help in identifying the specific source of the 1886 earthquake, it did constrain the resulting seismic hazard analysis and limited the likelihood that locations away from Charleston would be affected by large earthquakes.

A similar result surfaced in estimates of both seismic and volcanic hazards at the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. This site, in the Basin and Range tectonic province, lies in the vicinity of rare magnitude 6+ earthquakes and very infrequent volcanic activity. Many hypotheses were posed for the tectonic models that would explain earthquake occurrence or the location of future volcanism. Intensive work by the U.S. Department of Energy (DOE) and its contractors established both the timing and the location of past earthquakes and volcanic activity in such a way that reasonable alternative models had little effect on the estimated hazard. The collection of a broad and comprehensive database did not remove the uncertainty associated with tectonic models but essentially prevented it from being a serious stumbling block. This is not yet the case for another issue at Yucca Mountain, unsaturated zone flow and transport in fractured rock under present and future climatic conditions. This relatively new area of hydrogeologic investigation is of great importance in any calculation of the risk posed by the proposed repository. Although some progress has been made, efforts to establish a history of past flow-and-transport regimes in the unsaturated zone at Yucca Mountain have met with limited success. Dependence on competing models that are difficult to validate has downgraded initial strategies that relied heavily on natural barriers (i.e., geology) to contain and isolate the waste and increased the importance of engineered barriers in achieving these goals.

Estimating uncertainty

In a 1994 presentation to the NWTRB, Wendell Weart, chief scientist for the Waste Isolation Pilot Plant in New Mexico, made an observation that is particularly applicable to geologic investigations at many nuclear sites. He stated, "One is most confident of site and repository issues at the *beginning* [emphasis added] of detailed investigations." This has been particularly true for assumptions about hydrogeology at proposed nuclear waste repositories around the world. At Yucca Mountain, the original assumption was that the principal barrier to transport of harmful radionuclides from the repository would be provided by an underlying nonwelded tuff, the Calico Hills formation. This optimism was based on the assumption of very slow movement of groundwater thorough the rock matrix of this formation and the presence of transport-retarding zeolites within the rock matrix. Subsequent investigations revealed that much of this rock was fractured, allowing both fast flow and bypassing of many of the zeolites.

If one could compare the experience at a number of sites, the comparison would point to an initial expectation that as detailed investigations proceeded, uncertainties would be reduced gradually to the point where they no longer mattered. However, as site investigations progress, the amount of uncertainty often appears to increase. In reality, what occurs is the gradual realization that the *perceived* uncertainty at the beginning of a site investigation is much less than the *actual* uncertainty. Eventually, if investigations are sufficiently thorough, the perceived uncertainty begins to match the actual uncertainty and a better assessment of the site's true properties can be made, along with the development of a firmer basis for assessing the site's ability to perform its assigned functions. This misperception can contribute to the frustration of management and legislative bodies with overly optimistic schedules and the apparent decrease in confidence associated with ongoing investigations at some sites.

Dealing with uncertainties and surprises

Given that surprises do occur during geologic investigations and that uncertainties exist and even may increase, developing appropriate coping strategies is important. One such strategy is the use of multiple methods. For example, between the time units 2 and 3 of the San Onofre nuclear power plant in southern California received their construction permits and when they were reviewed for operating licenses, new information had been developed. This information included new and varying estimates of the length of the Offshore Zone of Deformation (OZD), the controlling fault for earthquake design (8 km from the site), and new methods for estimating earthquake potential from known faults. These methods included those related to total fault length, fault rupture length, fault area, and slip rate. Maximum magnitude was estimated using the different estimation methods. The estimates ranged from a low of magnitude 6.6 to a high of magnitude 7.3. Examination of the instrumental and historical record revealed that the largest event to occur on the fault or its hypothesized extensions was magnitude 6.8. Based upon this evaluation, it was decided that the controlling earthquake should be magnitude 7.0. The use of multiple methods of estimation prevented overreliance on any single one of a group of uncertain techniques. It is interesting to note that one of the techniques, the use of slip rate, is no longer considered appropriate. A similar approach was taken to estimating the ground motion from such an earthquake. In this case, empirical methods, newly developed numerical modeling techniques, and data from a recent magnitude 6.9 event in another part of California were used. Each of these techniques had its weaknesses: the empirical techniques were based on ground motions recorded at greater distances than that between the OZD and San Onofre; the numerical modeling techniques were in their infancy and contained assumptions that some considered questionable; and the recent earthquake data were from a slightly smaller earthquake recorded at site conditions different from those at San Onofre. Conservative (84th percentile) estimates from each of the techniques were compared and found to be relatively similar. Of particular importance is the fact that derived estimates of ground motion were all less than the original 0.67g earthquake design of the San Onofre plants.

Probabilistic analyses have also proven to be a particularly powerful means of dealing with uncertainty and surprises. Deterministic techniques, which rely on single scenarios and sets of parameters (e.g., in seismic hazard), do not reflect the uncertainty associated with that scenario or set of parameters, nor do they take into account the possibility of other less likely assumptions. The analysis could be based on a "worst case" scenario. Unfortunately, relying on the worst case when it is associated with a very low probability of being correct could, in many cases, lead to an "unwarranted" rejection of the site or increase in the cost of the facility. Judgment of what is a warranted or an unwarranted action is, of course, a societal decision, often referenced to an "acceptable level of risk," a criterion most easily used when explicitly defined in regulations. Uncertainty associated with the postulated locations where magnitude 7+ earthquakes could occur in the future and possible concerns with the safety of existing nuclear power plants along the eastern seaboard of the United States (discussed above) led to a particularly powerful use of probabilistic seismic hazard analysis (PSHA). This analysis was able to take into account the different tectonic hypotheses and developing data sets, such as those using sand blows described above. The calculated probabilities of exceeding the seismic designs of existing nuclear power plants provided a rational basis for decision-making. The analysis also led to the increased acceptance of PSHA in all subsequent decisions by the U.S. Nuclear Regulatory Commission.

Keeping it simple

Explaining geologic phenomena can be very complex, often involving the understanding and integration of basically different subdisciplines in physics, chemistry, and biology and applying this understanding to a very heterogeneous locale. As knowledge increases, quite appropriately the tendency is to rely on highly complex models to capture and match rapidly expanding data sets. Nuclear facilities, particularly those associated with radioactive waste that are required to project geological conditions hundreds and thousands of years into the future, are particularly subject to this increase in complexity. Although many describe this increase in complexity as necessary, it is not necessarily beneficial in making siting decisions or explaining the decisions to nontechnical audiences.

An illustration of this "contradiction" has been the proposed high-level radioactive waste repository at Yucca Mountain. As knowledge, for example, of the complexities associated with flow and transport in the unsaturated zone in Yucca Mountain under ambient and thermally and climatically altered conditions has been acquired, the models have become more complicated and difficult to explain. There is an anecdotal story of a chance encounter between a waste program manager and a high official of the DOE in an elevator. The high official asked the manager to explain how they proposed to achieve the safe disposal of radioactive waste. Difficulty in doing so before the elevator doors opened supposedly resulted in a recommendation that whatever the answer to that question is, it has to be boiled down to one that could be conveyed during a short elevator ride. Whether or not the specifics of that story are true, the Yucca Mountain project recently has devoted a great deal of effort to developing a simplified description of the scientific and engineering basis for safe disposal of radioactive waste at Yucca Mountain. It has isolated several key elements of this "strategy" and is concentrating work on these elements. Several oversight groups, such as NWTRB, also have urged the Yucca Mountain project to develop simplified calculations that would capture the essence of the more complex calculations. In a related consideration, Robert Budnitz, an experienced hand in nuclear affairs, has strongly urged that "analyzability" be a criterion in the evaluation of which engineering components should be chosen to help contain the waste. In other words, if a proposed engineered barrier to the release of harmful radionuclides to the environment is intuitively attractive but difficult to analyze, one may wish to look elsewhere. As William of Ockham put it over 600 years ago, "Multiplicity ought not be posited without necessity."

Sociopolitical considerations may override scientific ones

Sociopolitical considerations have been factors in some of the cases cited above. Nowhere, however, does the significance of such considerations become as obvious as they have been in attempts to site low-level radioactive waste disposal facilities. The previous example of Martinsville shows how a technical evaluation by a state-appointed commission rejected a site primarily because of its hydrogeologic characteristics. We present two examples in which state-appointed reviews reached conclusions that accepted a site but were rejected or questioned at a higher state or federal level. Sociopolitical concerns may have played important, if not overriding, roles.

After a screening process that looked at a number of locations, the Southwest Compact decided to site its low-level radioactive waste disposal facility in Ward Valley in the Mojave Desert in California. Following site characterization and preparation of an application to build and operate the repository, the regulatory body responsible for approving the site, the California Department of Health Services, reviewed the application and granted approval in 1993 for the construction and operation of the facility. Because the site was on federal land, the appropriate federal body, the U.S. Department of Interior (DOI) had to transfer the land to the state of California. At this time, in an unofficial capacity, three scientists at the U.S. Geological Survey (USGS) identified seven technical concerns having to do with the hydrological, geological, engineering, and biological aspects of the site that they felt had not been adequately addressed in the application. The DOI referred the issue to the National Academy of Sciences' National Research Council (NAS). A 17-person panel was convened and in 1995 reached its conclusions. The panel dismissed many of the issues, and 15 of the 17 members of the panel felt that any remaining uncertainty, mostly hydrogeological, raised by the three USGS scientists could be addressed during the development and early operation of the site, that is, work on the site could continue. The primary issue was the ability of radionuclides to migrate downward and eventually reach water resources. The NAS panel viewed this possibility as highly unlikely. Among other considerations, the panel pointed out that even if all the plutonium in the proposed repository were to reach the Colorado River (a primary source of drinking water), the level would be significantly lower than the levels of plutonium already in the river or permitted by accepted health-based standards. Environmental and local groups, along with some members of the California congressional delegation, argued against proceeding with site development. Eventually the DOI decided to hold up the land transfer until the uncertainties could be resolved. The 1999 GAO report implies that this decision was due more to politics than to science. After much delay, a newly elected governor decided to try pursuing alternative ways of disposing of California's low-level radioactive waste.

At about the same time, efforts were underway to site a low-level radioactive waste disposal facility for the Texas Compact near the town of Sierra Blanca in west Texas. Site characterization was concluded, and an application was submitted to the appropriate regulatory body, the Texas Natural Resource Conservation Commission (TNRCC). TNRCC technical staff conducted a review and issued a draft license approving the site. Hearings were held before administrative law judges (ALJ) in early 1998. They recommended that the license be denied, primarily because of concerns about a possible earthquake fault beneath the site. The technical review pointed out that the supposed fault was overlain by almost 200 meters of undeformed sediment at least 780,000 years old. The ALJ's based their rejection of the license application on the fact that very small deformations could not be detected in the underlying sediment and that there was not enough information on fault properties and possible connections to regional earthquake faults. The technical reviewers argued that sufficient work in these areas had been carried out to rule out such connections and that the existing seismic design of the facility was already conservatively set at a very high level (0.7 g), based on the possibility that a magnitude 6 earthquake could occur directly beneath the site and that a magnitude 7.0 earthquake could occur 10 km away. This is almost the same scenario and design level described above for the San Onofre nuclear power plant located in a much more seismically active region in Southern California. The technical reviewers argued further that even in the unlikely event that the facility failed as the result of an earthquake, analysis showed that the resultant dose would be significantly below regulatory criteria. In October 1998, the TNRCC commissioners, citing the earthquake concerns, denied the license request. Many have attributed this puzzling decision overriding the technical review to opposition to the project from Mexico (25 km away) and to political considerations before an upcoming statewide election.

Conclusions

Geology has played an important role in many siting and operating decisions for civilian nuclear facilities in the United States. Insights gained from past efforts emphasize the significance of choosing a good site, developing a broad data base, recognizing and dealing with uncertainty, and avoiding undue complexity. Geological issues have also highlighted the interactions among scientific, policy, and social issues, and the difficulty often faced in distinguishing between them.

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