POLICY FORUM: RADIOACTIVE WASTE

Less Geology in the Geological Disposal of Nuclear Waste

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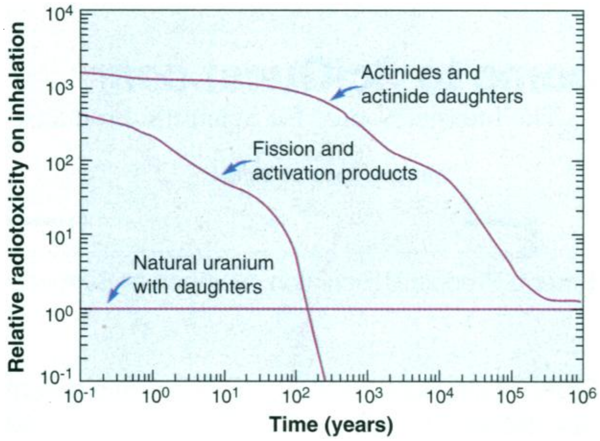
At the end of the 20th century, one of the most pressing problems, political and scientific, is the disposal and isolation of radioactive wastes (*1*). There is now a worldwide consensus (*2*) that effective long-term isolation for spent nuclear fuel and high-level radioactive or transuranic waste can be achieved by geologic emplacement. The chief elements of the geologic disposal strategy are as follows: (i) it was to be deep, permanent, and long term, using to advantage the decrease in radioactivity, thermal output, and radiotoxicity over time; (ii) the geologic history of stable regions was taken as indicative of future stability and continued suitability; (iii) the passive hydrologic and geochemical properties of the geologic formations were to be key to the isolation strategy. The large uncertainties in predicted future behavior were to be reduced by a system of independent, multiple barriers, geologic and engineered. However, the present approach in the United States, as embodied in proposed rules and standards, moves away from the fundamental precepts of geological disposal.



Relative radiotoxicity on inhalation of spent nuclear fuel with a burnup of 38 megawatt-days/kg uranium (*12*). The radiotoxicity values are relative to the radiotoxicity (horizontal line) of the quantity of uranium ore that was originally mined to produce the fuel (8 tons of natural uranium yields one ton of enriched uranium, 3.5% 235U).

In the United States, two sites have been selected for geologic disposal. The Waste Isolation Pilot Plant (WIPP) in New Mexico now receives transuranic wastes generated by defense programs. The Yucca Mountain site in Nevada has been under active investigation for a quarter of a century as a site for the disposal of high-level wastes, more than 90% of which will be spent fuel from commercial power plants. The Nuclear Regulatory Commission (NRC) has recently proposed rules for implementing the standards for the disposal of high-level waste at Yucca Mountain, and the Environmental Protection Agency (EPA) has just released the radiation protection standards for Yucca Mountain. The EPA is responsible for developing "generally applicable standards" for the repository, and the NRC is responsible for promulgating rules or regulations, which if complied with, will ensure that EPA's standards are met. The new rules and standards rely on a probabilistic performance assessment (PPA) of the repository to provide a single quantitative measure of compliance. This approach, when combined with a proscribed compliance period that is short compared with the time for geologic or climate change (10,000 years), a point of compliance that is far from the site (20 kilometers), and the elimination of performance standards on separate barriers, represents a significant deviation from the original concept of long-term geologic disposal.

The concept of geologic disposal began in the 1950s and over the next 30 years evolved with the publication of criteria for a geologic repository (*3*) and an analysis of the types of information that would be required and the complexity and uncertainties inherent in a safety analysis of a geologic repository (*4*).

The Nuclear Waste Policy Act of 1982 represented a clear commitment to permanent geologic disposal and provided for the investigation of three sites that represented a variety of rock types (bedded salt, basalt, and volcanic tuff). However, the investigation of multiple sites proved to be expensive and time-consuming, and in 1987, Congress (in the Nuclear Waste Policy Act Amendments) limited Department of Energy (DOE) focus to a single site, Yucca Mountain in Nevada. In 1992 (Energy Policy Act), Congress directed that the EPA prepare standards specific to Yucca Mountain and that EPA arrange for an analysis by the National Academy of Sciences (NAS) of the technical basis for proposed standards (*5*). Thus, geologic disposal of high-level nuclear waste in the United States is now discussed in the context of a single site and site-specific standards. Approximately 3 billion dollars have been spent on studies of the proposed Yucca Mountain site, and considerable responsibility and pressure rests on the shoulders of all involved federal agencies. In 1998, DOE completed a total system performance assessment–viability assessment (TSPA-VA) and has reported to Congress that there are no "showstoppers." Work proceeds toward a license application as a repository in 2001.

Probabilistic performance assessment

During recent years, there has been a move toward "risk-informed, performance-based regulation" (*6*), and this approach combined with the analysis of total system performance is now the key to licensing a nuclear waste repository. The PPA methodology, as applied to geologic disposal of nuclear waste, has developed from roots in probabilistic risk assessments of nuclear reactors (*7*). There is no doubt that PPA (for example, the recent TSPA-VA of Yucca Mountain) is an essential and highly informative method for analyzing complex systems and focusing work and resources on their most important elements.

Although PPA is useful, PPA modeling of the complex behavior of a geologic system over extended periods of time has not been shown to be effective. The limitations of PPA are especially important when it is applied to natural systems for which there is a sensitive dependence of the final result on initial or bounding conditions (*8*). In such "chaotic" systems, errors and uncertainty may increase exponentially with time. A typical PPA of a repository contains hundreds of subsystem models (often highly simplified descriptions of the physical and chemical phenomena), requires thousands of input variables (fixed and sampled over ranges, many based only on expert opinion), and often does not account for nonlinear coupling between important elements of the system. If the PPA is to be the single quantitative criterion, then it is essential to distinguish between a result that is driven mainly by assumptions

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about boundary conditions (for example, climate change and assumed rates of human intrusion) versus the actual properties and behavior of the repository (such as sorptive capacity). If the results of the PPA depend mainly on assumed boundary conditions that are often probabilistic, then the geologic properties of the site have little bearing on the analysis.

Actual experience with specific subsystem models of hydrologic and geochemical processes has shown how disappointingly unpredictive they can be (*7*). The uncertainties in the fundamental database, knowledge of the site, conceptual models, expert opinions, probabilities assigned to initiating or bounding events, and knowledge of the effects of coupled phenomena on the total system performance pose serious obstacles to a convincing demonstration of compliance (*7*). Each of these uncertainties will propagate through the PPA, and although the different types of uncertainty can be described mathematically (*9*), little has been done to test the methodology against the behavior of actual geologic systems. The large uncertainties could obscure the analysis of the performance and mask the actual environmental and health impacts of the repository.

Multiple barriers

One early tenet of geologic disposal was that uncertainties in the assessment would be large, but could be reduced by requirements placed on individual geologic or engineered barriers (such as release rates of radionuclides, groundwater travel times). The present NRC rulemakings substantially reduce the importance of multiple barriers by eliminating specific performance standards. This is partly because it is difficult to identify truly independent barriers in a repository system. Another argument against performance criteria for individual barriers has been that performance specifications for subsystems can lead to less than optimal design and performance of the total system. In the extreme, such an argument is inherently illogical. An inert waste form that does not release radionuclides would improve total system performance. The absence of groundwater flow in the unsaturated zone (above the water table) would not allow release of water-borne nuclides. In real life, however, there is no "silver bullet," and each subsystem may fail to some degree over extended time. No subsystem can (or should) account for the total system performance; however, a system of arguably independent barriers (for example, the corrosion rate of a canister in the unsaturated zone is not closely related to the flow-rate in the saturated zone) can reduce uncertainty and increase confidence. More important, in a complicated system, components are more easily analyzed than the whole. If the components cannot be analyzed, then the analysis of the total system is not made more tractable or useful by combining the subsystem models in order to obtain a single quantitative measure of successful performance.

Most important, understandable and clear subsystem requirements may contribute to increased public acceptance. A geologic repository for which travel times to the accessible environment are less than 1000 years or waste package release rates are in excess of reasonable materials science performance standards is certainly not acceptable, regardless of the positive results of a "quantitative" PPA.

Compliance period

The compliance period of 10,000 years is based on three considerations: the decay of short-lived fission products will substantially reduce the activity; the period is long enough to capture the essential performance features of the repository; extrapolation of models beyond 10,000 years is unrealistic. Although there will be a substantial reduction in radioactivity during the first 10,000 years, the repository will still contain substantial quantities of long-lived fission products and actinides that continue to contribute to elevated exposures (see graph on page 415). The recent TSPA-VA of Yucca Mountain showed that the highest levels of exposure due to ^{237}Np, ^{239}Pu, ^{99}Tc, and ^{129}I occurred well after 10,000 years. The NAS committee that examined the technical basis for the Yucca Mountain standards recommended that the compliance assessment be extended to the time when the highest risk occurs (*5*). This is typically well beyond 10,000 years. Selecting such a short period, with no analysis extending beyond 10,000 years, has the effect of eliminating from consideration the effects of events, seismic and volcanic, that occur at low probabilities.

Point of compliance

The total system performance of a repository is taken as a measure of dose to an individual or critical population at some distance from the repository; in the case of Yucca Mountain, this distance has been set at approximately 20 km. Such a calculation is appropriate and reasonable in the evaluation of risk, but it has little to do with the performance of the underground facility. The calculation of risk is qualitative, again because of the large inherent uncertainties. In order to effectively compare different repository designs or disposal strategies at a single site, the calculation of radionuclide release should be made over a much shorter distance in order to emphasize the properties and performance of the repository. The attractiveness of the Yucca Mountain site was, at least initially, based on its location in an arid environment and the absence of flowing groundwater in the unsaturated zone. On the basis of the present approach, the site may now be judged to be acceptable because of retardation, dispersion, and dilution effects during transport over the 20-km path to the point of compliance.

The sole reliance on PPA to provide a quantitative criterion, in conjunction with the elimination of performance standards for individual barriers, the geologically short compliance period, and the extended distance of the point of compliance all combine to reduce substantially the role of the geologic properties of the repository in the waste containment strategy. Such a shift in approach does little to build public confidence in the repository site; however, as others have noted, the "U.S. geologic disposal program is making a last stand at Yucca Mountain" (*10*). This last stand now relies heavily on engineered barriers (for example, zircaloy cladding and extended waste package lifetime) and the probabilistic analysis of their behavior during the first 10,000 years (*11*). The conclusion that there are no insurmountable obstacles in the present strategy and analysis begs the question of whether Yucca Mountain provides effective geologic barriers to radionuclide release and whether the present analysis provides the resolution required to recognize a showstopper.

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