NUCLEAR WASTE

Proof of Safety at Yucca Mountain

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It has long been recognized that the physical and chemical interactions associated with placing heat-generating nuclear waste in a geo-hydrologic environment are complex and difficult to predict (*1*) and that proof of safety in an absolute sense is beyond reach. The fundamental problem of the Yucca Mountain nuclear waste repository project, for which the life-cycle cost was last put at over $57 billion (*2*), is its lack of a robust proof of safety for a period of hazard of a half-million years or longer. Proof of safety calls for a design of relative simplicity based on well-understood physical and chemical phenomena, careful testing and measurement, and adequate theory for extrapolations. The "proof" ultimately lies in performance assessments showing such low radiation doses as to indicate that throughout the period of hazard essentially all radioactive elements are contained near the point of waste emplacement. In our view, the present repository design cannot meet these tests.

To understand this, it is important to appreciate the Environmental Protection Agency's evolving radiation protection standards for the Yucca Mountain project. In June 2001, the EPA issued standards setting the maximum allowed dose at 15 millirems (mrem) per year but limiting compliance assessment to 10,000 years. These standards were invalidated by the U.S. Circuit Court of Appeals for the District of Columbia in its ruling of 9 July 2004. The court found that the EPA, by limiting compliance assessment to 10,000 years, had failed its statutory obligation to heed recommendations of the National Academy of Sciences. An academy panel (*3*) had found that "peak risks might occur tens to hundreds of thousands of years or even further into the future" and that performance assessments would be feasible.

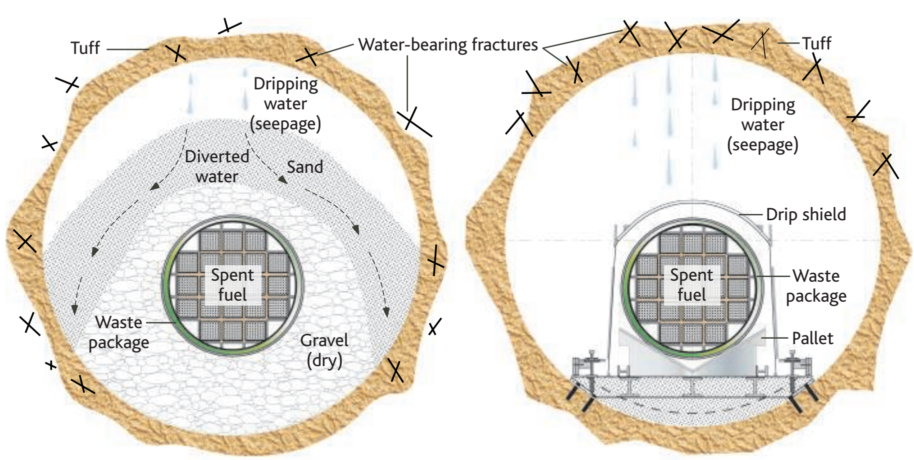
In response to this court ruling, the EPA issued for public comment this past 9 August a proposed new standard that would establish a two-tiered radiation-protection regime, with a 15-mrem/year maximum dose for the first 10,000 years and a 350-mrem/year dose for up to 1 million years thereafter. If this proposed standard is adopted, licensing may become easier, but credibility of project performance assessments will continue to face serious challenge.

The Total System Performance Assessment (TSPA) issued by the project in December 2001 (*4*) was a key input to the documents supporting the formal selection of the Yucca Mountain site and the joint resolution by Congress upholding that selection after the state of Nevada exercised its right to veto it. The TSPA did not, however, promise virtually total containment of radioactive elements out to hundreds of thousands of years. The waste containers are to be protected by two major engineered features: first, a corrosion-resistant outer layer of the nickel-based alloy-22 and second, a massive and continuous "drip shield" of titanium to be installed over the containers just before closure of the repository, about a hundred years after emplacement of waste in the repository has begun (see figure below). The performance assessment showed the containers and the drip shield beginning to fail within the first several tens of thousands of years (*5*). How, then, could safety be assured over times vastly longer than that?

A plume of groundwater contaminated by radioactive elements would form beneath the repository and would migrate southward down the hydraulic gradient, passing, over time, through the shallow aquifers of Armagosa Valley, where there is currently irrigated farming. Radiation doses above the usual regulatory limit of 15 mrem/year would begin to occur after about 200,000 years (*6*).

Even a new TSPA could not get around the fact that the preferred design does not match characteristics crucial to establishing proof of safety. It is not a simple design: The titanium drip shield itself adds substantial complexity to repository design and construction. Consider the 100-year delay (*7*) in installation of the drip shield. Will decision-makers four generations hence, with priorities unlike our own, choose to install a feature which in year-2000 dollars would add several billion dollars to project costs?

The project's most complicating feature is its preferred "hot repository" option, whereby waste containers would be spaced closely enough for the heat from radioactive decay to bring the water in the nearby rock above the boiling point. The water would become water vapor and migrate outward, away from the waste emplace-



Proposed storage of nuclear waste at Yucca Mountain repository. (Left) Current DOE disposal design (*4*), including nuclear waste package and overlying titanium drip shield within an open tunnel. **(Right)** Capillary barrier design (*8*), in which the difference in permeability and capillary properties between two backfill materials assures diversion of groundwater flow around the waste packages (no drip shield needed).

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ment tunnels. But complicated flows of air, water vapor, and liquid water would be created, and chlorides and other corrosive chemicals would be mobilized by water reacting with the hot rock. This design feature is puzzling, because it could do nothing to prevent corrosion of waste containers beyond the first 10,000 years when the repository will have cooled from the declining levels of radioactivity.

Is the design based on well-understood physical and chemical phenomena? Does it allow reliable testing and measurement, and is there adequate theory for extrapolating far beyond real-time data? To these questions, too, the answer is no. The project design team has worked hard on safety, but the drip shield, the container's alloy-22 outer shell, and the preferred hot repository design appear to have been chosen in an ad hoc manner.

What would be a better repository design? First, the design must be carefully adapted to the specific characteristics of the site. At Yucca Mountain the repository would be built within a mountain ridge of volcanic tuff that is high above the water table in "unsaturated" rock where the water present, although there is plenty of it (100 liters per cubic meter), does not fill all the pores in the rock (*8*). In this unsaturated or vadose zone, water moves quickly through open fractures but its movement within pores in the rock is kept extremely slow by the capillary tension between air and water in a tightly confined space.

In this setting, the repository would be relatively dry and accessible by gentle ramps and tunnels from the flanks of the mountain ridge. But an accompanying disadvantage is that air moves freely through the mountain via interconnected open and dry fractures permeating the ridge. Thus, waste containers may corrode whenever they become wet or damp.

A design strategy (*9, 10*) that would appear to have an excellent chance of satisfying a robust proof of safety is based on a man-made capillary barrier (see figure, page 447). The waste containers would be covered first by a layer of coarse gravel, then by a layer of fine sand or finely ground tuff. This barrier would work by virtue of the strong capillary forces present in the sand layer and by their absence in the gravel layer. Water dripping from the tunnel ceiling onto the sand layer would be seized by capillary forces and caused to move very slowly away through the sand above the gravel. The gravel layer is the key to computing radiation safety over the long term.

All the waste containers beneath the gravel will corrode over time from the water vapor and oxygen present. Eventually, radioactive elements dissolved in water will emerge from the failed containers, diffuse along the gravel particle surfaces, and, as we infer from a performance assessment of 10 years ago, remain trapped there for hundreds of thousands of years. This assessment predicted that the radiation dose to future people from a repository using a capillary barrier would be lower at all times by a factor of one million than the dose from a repository similar to the one envisioned by the Yucca Mountain project today (*11*).

By comparison with the project's present reference design, the capillary barrier system would be far simpler. It would also be far cheaper, from a use of locally obtainable materials, without need for either the alloy-22 outer shell for the containers or a costly drip shield. The average cost for each of the 14,700 waste packages, with drip shield, would be about $900,000 (*7*). Given the intense radioactivity present, installing a drip shield or a capillary barrier would almost certainly entail remote handling, but the capillary barrier would be easier and cheaper. The capillary barrier concept remains untried for disposal of spent fuel or high-level waste, although there has been international experience with capillary barriers for disposal of low-level radioactive waste. There should also be tests of barrier integrity under earthquake forces, but ground shaking would be greatly attenuated deep in a geologic repository (*12*).

Another design concept worthy of serious exploration at Yucca Mountain is that of using depleted uranium in waste containers as a sacrificial material to protect the spent fuel. But finding a predictably enduring corrosion-resistant material could be critical, because proof of safety might turn on showing experimentally that failure of the container will not be by general corrosion but by pitting or pinholes. Oxidation of the depleted uranium should in that case occur slowly enough for the spent fuel to be protected from degradation for hundreds of thousands of years. The U.S. Department of Energy (DOE) has enormous stocks of depleted uranium from past uranium enrichment, and this material could be used in casks for storage and transport of spent fuel (*13*) but rigorous testing for its use in casks for final disposal has not been done.

If the Yucca Mountain project should be rejected or abandoned, continued storage of spent fuel in surface facilities is the default option. The most likely new place for such storage is in Utah where, on 9 September 2005, the U.S. Nuclear Regulatory Commission (NRC) denied the state of Utah's appeals to stop a nuclear industry initiative to store fuel on the Skull Valley Goshute Indian reservation (*14*). The availability of this new storage center, where older fuel from many of the 65 widely scattered reactor stations could go, should make for a better Yucca Mountain repository project by dampening legal and political pressures that might otherwise lead to undue haste in design work and the supporting experimentation.

Conditions similar to those at Yucca Mountain are found in rock types around the world wherever there is an arid climate, substantial topographic relief, and a deep-lying water table. Success at Yucca Mountain could powerfully suggest that hosting disposal of spent fuel and high-level waste can be a safe and profitable use for terrain previously deemed a wasteland, and that siting repositories in the future will be much less difficult than it has been in the past. The restraints on a global resurgence of nuclear power in response to growing energy demand and concerns about greenhouse warming are, to be sure, not limited to waste disposal. Nonetheless, a proof of safety for such disposal that is seen internationally as highly robust might relieve a matter of vexing and persistent concern.

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