In Search of Water: An Update on Yucca Mountain Studies
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Design and fabricate a system that will last thousands of years longer than the recorded history of humankind. Make that system robust enough to isolate highly radioactive material so that it will not threaten human health and the environment for millennia.

Unprecedented challenge or daily task? Both — the “system” is Yucca Mountain, the federal government’s candidate site for the disposal of high-level radioactive waste and spent nuclear fuel. The Department of Energy (DOE) Yucca Mountain Site Characterization Office’s mission is to “provide the basis for a national decision regarding the development of a repository for spent nuclear fuel and high-level waste at Yucca Mountain.” The natural and engineered features are expected to work together to isolate the wastes from the public and the environment for more than 10,000 years, as required by law.

Yucca Mountain lies in Nye County, Nev., about 100 miles from Las Vegas. Since 1982, the Department of Energy has been working to determine its suitability as a site for storing high-level nuclear waste. On Feb. 15, President Bush approved Yucca Mountain as a nuclear disposal site. Image courtesy of the Department of Energy.

Congress charged DOE (in the Nuclear Waste Policy Act of 1982 as amended) with this task almost 20 years ago. Now, completion is years away, but on Feb. 15, President Bush approved Yucca Mountain as the nation’s geologic repository. In January, the Secretary of Energy notified the Nevada Governor that he intended to recommend to the president that the site be developed as a repository. The final decision in this complex process could make the site the nation’s first deep geologic, high-level radioactive waste repository.

The geology of Yucca Mountain is critical to containing the radioactivity present in spent nuclear fuel and high-level radioactive waste. Water in the geologic setting is the primary medium by which radioactivity could escape.

The requirements to limit the release of radioactivity to the accessible environment are spelled out in regulations and guidelines set forth by the U.S. Environmental Protection Agency, the U.S. Nuclear Regulatory Commission and DOE. Preliminary performance estimates for the expected evolution of the system indicate that the mountain itself (the natural system) is capable of isolating over 99 percent of the radionuclides that would be placed in the repository. The disposal cask, or waste package, and the rest of the engineered system provide for the remaining 1 percent. Defense in depth also assures compliance.

These regulations require that we evaluate the expected and the unexpected geologic evolution of the system. Expected events include seismic activity that would cause rock falls in the repository’s drifts, or storage tunnels, with minor consequences. An example of something unexpected would be a volcanic event, such as a dike intersecting the repository, which has a mean likelihood of occurrence of approximately one chance in 62 million per year. Such an event is evaluated in terms of potential consequences. The regulations require that these consequences, multiplied by their likelihood, be below a specified target value. Evaluations performed to date suggest it is highly likely that a

http://www.agiweb.org/geotimes/mar02/feature_water.html
repository at Yucca Mountain would be able to meet the specified safety target for both its expected and unexpected evolution scenarios.

The expected evolution of the repository system at Yucca Mountain will rely on two geologic barriers: the volcanic rock above the water table, called the unsaturated zone barrier; and the volcanic rock and alluvium below the water table, called the saturated zone barrier.

**Unsaturated zone**

The host rock (welded tuff) that defines the repository horizon is in the unsaturated zone, approximately 1,000 feet below the crest of Yucca Mountain and approximately 1,000 feet above the water table. The thickness of the unsaturated zone provides a significant barrier to long-term rises in the water table induced by climate change or transient seismic activity. The repository would reside within this unsaturated zone where the waste packages would be placed in tunnels called emplacement drifts and excavated within layers of the unsaturated welded tuff.

Yucca Mountain is an uplifted ridge of alternating layers of welded and non-welded silicic volcanic tuffs of Miocene age. The degree of welding of the various tuff units determines how water moves through each particular unit. Generally, water predominantly flows through fractures in the welded units, while it tends to flow through the matrix of the non-welded units.

On the most fundamental level, the factors affecting unsaturated groundwater flow at Yucca Mountain are the climate and the hydrologic properties of the rocks. Derived from these two basic factors are estimates of two key unsaturated zone processes: deep percolation flux and potential seepage into waste emplacement drifts.

Temperature also plays a part. The conditions within the drift environment and the potential transport of radionuclides from the repository horizon must be considered for both ambient and thermally affected scenarios. Specifically, the heat given off by the decay of the spent fuel will raise the temperature of the repository environment and will affect the ambient flow field in various hydrologic, chemical, and mechanical ways.

The Unsaturated Zone Flow, Transport, and Coupled Processes Model is the tool for investigating the wide range of processes that can affect the natural system of the repository. This overarching model integrates a number of separate modeling efforts that address a variety of physical, hydrologic, thermal and chemical phenomena. These sub-models include a geologic framework model; models for climate and infiltration; unsaturated zone flow; drift seepage; radionuclide transport; a mountain-scale model of thermal-hydrologic, thermal-hydrologic-mechanical, and thermal-hydrologic-chemical interactions; and a drift-scale model of thermal-hydrologic and thermal-hydrologic-chemical interactions.

Sub-models are abstractions of reality. Each one differs in complexity, depending on its impact or on its associated uncertainty about overall system performance. Sub-models are working hypotheses, which are consistent with existing knowledge, but which scientists are continually re-evaluating for adequacy over time as new knowledge becomes available.

Inputs for these models come from many sources: geologic and fracture maps (made from boreholes, drifts and outcrops); climate records and infiltration measurements; in-situ hydrologic measurements (air permeability, fracture porosity, saturation and water potential); laboratory hydrologic measurements (matrix permeability, porosity and capillary pressure); tests for seepage, flow and transport; thermal testing; and geochemical, isotopic and mineralogical measurements.

Subsurface testing continues within several alcoves and niches of the Exploratory Studies Facility (ESF) and Cross Drift to gather additional data to refine the drift seepage model. Niches are short drifts, typically 10 meters long, that branch off the ESF or Cross Drift and are used for testing whether emplacement drifts can effectively contribute to limiting potential drift seepage. The capillary barrier mechanism and the seepage threshold concept — the amount of percolation flux below which no seepage into a drift occurs — have been investigated. DOE is adopting a conservative
DOE is collecting additional data relevant to seepage modeling with regard to spatial and temporal flow focusing, the zone disturbed by excavation, drift geometry and drift surface effects, ventilation and evaporation-condensation effects, and thermal effects and coupled processes.

The engineered barrier system incorporates a component designed to add an additional layer of safety for the waste packages. This barrier is a drip shield composed of titanium. It will extend over the waste packages and block any seepage. The barrier system will also provide protection for the waste packages from rock falls produced by drift degradation.

A large-scale experiment to monitor moisture is underway within the Cross Drift. The last third of the Cross Drift has been sealed for nearly three years, with the exception of periodic entries to observe and collect potential seepage below the crest of Yucca Mountain and under the hill slope associated with the Solitario Canyon fault, host to suspected zones of high infiltration. The objective of this effort is to see if any seepage is observed under ambient (unventilated) conditions. To date, no confirmed seepage has been observed. All water samples collected have been shown to exhibit a chemical composition consistent with water condensing due to temperature gradients resulting from machinery heat sources.

Other ongoing studies are providing valuable data for systematic hydrologic characterization of potential repository host rocks, the diffusive properties of faults in response to various tracers, and estimates of seepage potential using calcite abundances. Also ongoing are corroborative studies of bomb-pulse isotopes (chlorine-36 and tritium), pore water chemistry, fluid inclusions and oxygen isotopes, unsaturated zone transport, and natural analogs.

The testing program for unsaturated zone flow and transport continues to update the information needed for better calibration, validation and assessment of models showing how water flows and how radionuclides may be transported through the unsaturated zone. We are refining and improving our understanding of the unsaturated zone attributes that contribute to the waste isolation capacity of Yucca Mountain in order to achieve more realistic representations of the unsaturated zone system with drift-scale to site-scale models.

The new information strengthens the effort to determine whether the water potentially seeping into the drifts is limited in amount and whether the modeled concentrations of radionuclides moving through the volcanic tuff below the repository can be more accurately calculated. With limited seepage and, subsequently, reduced radionuclide concentrations capable of being transported, the unsaturated zone could be a more effective barrier than our initial, conservative modeling approach suggests.

Although not all testing of the site has been completed, the wide range of studies to date generally indicate that the combined attributes of the natural system plus various engineering design enhancements can successfully provide a suitable environment for the safe emplacement and isolation of waste.

Saturated zone

Assessing the performance of the total repository system includes evaluating the potential for radionuclides to migrate through the saturated zone underlying Yucca Mountain and from there migrating into the accessible environment. While the host rock of the unsaturated zone offers essential protection to preclude transport of radionuclides to the accessible environment, the radionuclides would first have to pass through the waste package and engineered barriers. Radionuclides cannot escape the repository until the waste package and waste form deteriorates. Only then could they start their vertical movement from the unsaturated zone and down into the water table and saturated zone.

The saturated zone at Yucca Mountain is another component of the natural barrier system affecting the transport of radionuclides to the biosphere. Evaluations of the zone’s long-term behavior take into account the effects of climate changes, with water table rise and increased flux being the saturated system’s response to a wetter climate.
The physical processes relevant to groundwater flow and radionuclide transport in the saturated zone are advection, dispersion, sorption, matrix diffusion, colloid-facilitated transport, and radioactive decay and the ingrowth of decay products.

Groundwater flow in the saturated zone at Yucca Mountain initiates in volcanic tuffs and transitions into alluvium. Physical processes in the volcanic aquifer and the alluvial aquifer have different effects on the fate and transport of radionuclides. The volcanic sequence is dominated by fractured media, and the groundwater mainly travels through these fractures. Physical transport properties in the volcanic media involve advection and matrix diffusion. Sorption can occur on fracture coatings and on the rock matrix.

The alluvial aquifer system is currently modeled as if it were a single porosity continuum. This continuum has a larger effective porosity than the volcanic system, which means the models show the groundwater traveling more slowly through it. Testing is in progress that will either support the current modeling or allow more realistic modeling of groundwater paths through the saturated zone. Transport properties important to the alluvial system are advection, dispersion, and sorption.

The Yucca Mountain Project hydraulic and tracer testing programs test conceptual models of flow and transport in the volcanic and alluvial aquifers and obtain flow and transport properties of the media. The C- Wells complex was developed for testing in the volcanic system. Testing at the C- Wells complex was completed in 1999. The alluvial testing complex (ATC) was developed for testing the alluvial flow system. Single well tests were completed in 2000, while multi-well testing was initiated in 2001 and is continuing to date.

The C- Wells testing program consisted of initially performing a series of single-well and multi-well hydraulic aquifer tests to determine flow properties of the fractured system. Open-hole and isolated interval aquifer tests were performed on multiple wells. Through these hydraulic tests, researchers determined the flow parameter ranges and designed tracer tests. Tracer testing at the C- Wells complex consisted of a series of forced gradient tests in which conservative (non-reactive) and reactive tracers were used to simulate radionuclide transport. In addition to tracer testing using the conservative and reactive tracers, additional testing was performed to test colloidal transport of radionuclides through the use of polystyrene microspheres. Conservative microsphere testing, in conjunction with laboratory colloid analysis, allowed made it possible to determine colloid filtration potential. With the additional laboratory analysis, colloid reaction models were developed to determine sorption kinetics for reversible and irreversible reactions and transport potential.

These C- Wells tests helped in confirming a model of a system driven by both fracture flow and matrix diffusion. Testing developed a range of flow and transport parameter values such as fracture porosity, effective diffusion coefficients and sorption coefficients.

The tracer-testing program at the ATC consists of single- and multi-well tracer testing programs, where the C- Wells testing program included only multi-well tracer testing. Single-well testing has been completed while multi-well testing at the ATC began in late 2001.

Single well testing began with the performance of isolated interval and open well hydraulic aquifer tests for the purpose of obtaining flow parameters and designing single and multi-well tracer tests. Single-well tracer tests involved the injection of conservative, reactive, and microsphere tracers into one well. Tracers were forced into the formation through the injection of chase water. Two tests involved varying tracer drift periods before pumping back into the well. One test involved immediate pumping. Single-well testing confirmed the single porosity behavior of the alluvial aquifer. The ATC test program is a collaborative effort with Nye County, the situs for the proposed repository. The
county is involved in studies to help understand the saturated zone.

Multi-well tracer testing was initiated in 2001 with the performance of isolated and open-hole aquifer tests to quantify additional hydrologic parameters (transmissivity, hydraulic conductivity, and storativity). Forced gradient tracer tests will be performed using conservative, reactive, and microsphere tracers similar to that performed for the C-Wells tests. Injection will occur in two wells with a single pumping well. Objectives for the multi-well tracer testing will be to verify parameters obtained through single well testing, verify conceptual flow and transport models, develop in situ alluvial transport parameters (effective flow porosity, longitudinal dispersivity, sorption, mass transfer (alluvial equivalent to matrix diffusion), and colloid transport parameters.

Studies to date indicate that the geology of Yucca Mountain forms its own complex system. Understanding the unsaturated and saturated zones has been critical to predicting the ability of the repository to meet containment guidelines and release standards. Some level of uncertainty will always exist. Studies would not terminate with site recommendation, license application or even operation of the potential repository. DOE scientists would seek to validate their predictions of containment performance by conducting performance confirmation, a set of tests and analyses activities that check, and perhaps confirm, the interpretations of work done to date. Performance confirmation and other testing would continue until the repository is closed, and perhaps even beyond that time.

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