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June 27, 2003

U.S. Nuclear Regulatory Commission
ATT: Deborah DeMarco
Office of Nuclear Materials Safety and Safeguards
Two Whiter Flint North
Mail Stop 8 A23
Washington, D.C. 20555

Subject: Submittal of an Article for Programmatic Review: Safety in the (Very) Long Run Assessing Long-Term Performance of a Geologic Nuclear Waste Disposal Site

Dear Mrs. De Marco:

The purpose of this letter is to transmit to the U.S. Nuclear Regulatory Commission (NRC) the subject article for a programmatic review. This approved article will be published in the July issue of Technology Today, a publication of the Southwest Research Institute®. Results reported in this article are taken from the previously published paper titled, "Independent Postclosure Performance Estimates of the Proposed Repository at Yucca Mountain, Nevada," the proceedings of the 10th IHLRWM Conference, Las Vegas, Nevada, March 30 through April 14, 2003.

Should you have any questions regarding this, please contact Dr. Sitakanta Mohanty at (210) 522-5184.

Sincerely,

Budhi Sagar
Technical Director

SM/rm

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Safety in the (Very) Long Run

Assessing Long-Term Performance of a Geologic Nuclear Waste Disposal Site

by

Sitakanta Mohanty, PhD

The monumental pyramids of Egypt, built around 5,000 years ago, survive into the present as some of the oldest manmade structures on earth. Even these failed their intended purposed: surface stonework was damaged or removed, and the treasures inside were stolen. Contrast this with a modern-day project to build a repository so safe and strong, yet so inconspicuous and remote, that it would isolate humankind from some of the world's most toxic nuclear waste for twice as long as the pyramids have stood.

Like the pyramids, the new project is to be located in an area of dry climate. It is designed such that its subterranean waste storage packages will be long-lived and that should any releases of radionuclides occur in the future, they will be small and slow spreading. Also, the designers of this high-level nuclear waste repository emphasize public safety and the ability to communicate to future generations a message that is in stark contrast to the pyramids' romantic allure.

In 2002 the White House and then the Congress formally approved Yucca Mountain (Figure 1), in Nevada, as the site of a geologic repository for spent nuclear fuel and high-level nuclear waste and recommended the Department of Energy to seek a construction authorization from the U.S. Nuclear Regulatory Commission (NRC) for the repository. The recommendation followed two decades of congressionally mandated research involving an array of scientific and technical disciplines to ensure the long-term safety and integrity of the site. The NRC, which has responsibility for developing regulations to implement the Environmental Protection Agency safety standards and for licensing the repository, has established the federally funded Center for Nuclear Waste Regulatory Analyses (CNWRA) at Southwest Research Institute** (SwRI*) to

provide technical assistance and research.

High-level Radioactive Waste

A total of 70,000 metric tons of radioactive waste is to go to the proposed Yucca Mountain repository[1]. Although most will be spent nuclear fuel from civilian electricity-generating reactors, numerous other types of nuclear waste are to be disposed, including the byproducts of reprocessing spent nuclear fuel, high level waste from defense activities and hundreds of other special waste forms from research and other activities. Prior to storage, some high level waste will be vitrified, or heated and mixed with other materials to form glass, then poured into steel waste packages. The spent nuclear fuel will be disposed as it is when it comes out of the power plant, in the form of pellets, stacked and sealed in metal alloy tubes called cladding.

If improperly handled, the high level waste can be deadly. While a fatal whole-body dose for humans is about 5 sievert (Sv) (500 rem) of acute exposure, the surface dose rate for a typical spent fuel assembly still exceeds 100 Sv (10,000 rem) per hour, 10 years after removal from a reactor[2]. Radioactive isotopes will eventually decay to harmless materials, even when stored at current temporary facilities such as the large water-cooled pools at nuclear power plants. However, it would be a very long time before they are harmless, and as they decay they emit radiation. Some isotopes decay in minutes, hours or days while others decay very slowly. For example, thorium-234 has a half-life of 24.1 days, while uranium-238 has a half-life of 4.5 billion years. Therefore, the wastes must be stored at a site that adequately isolates them from human beings for a very long time.

Yucca Mountain's proposed design would provide twofold protection through a system of natural and engineered barriers. The natural system capitalizes on the site's geology as well as its desert climate, sparse vegetation and relatively low population density. The main attributes for the natural system are the

surrounding rock's ability to slow down the movement of water, chemically remove radioactive particles from contaminated water and hold them in place, and the 12-mile distance that radioactive particles would have to travel through the rock before reaching an area where water is likely to be used by anyone.

The engineered, or man-made, system is proposed to be embedded in the geologic medium (Figure 2), nearly halfway between the land surface and the water table approximately 600 meters below the surface, to add a second barrier against release and migration of radioactive materials. The engineered system consists primarily of a corrosion-resistant waste package covered with a metal shield to prevent water and chemicals from dripping on and entering the waste package. The waste packages would be stored on stands so that pooling water will not contact them. Between 8,800 and 12,000 waste packages are expected to be used for disposal.

Performance Assessment

Estimating the performance of any underground repository is a complex exercise with substantial uncertainties, an extremely long period to be analyzed (at least 10,000 years), and the need to assess the robustness of manmade structures despite relatively little experience with the materials to be used. A computer model is needed to estimate performance over such long periods. Any detailed computer modeling must consider all possible scenarios: earthquakes; coupling among thermal, hydrological, chemical and mechanical processes; spatial variations in the emplacement of the waste form; rock physico-chemical properties; uncertainty in the process; various conceptual models; and the likelihood that possible future events will actually occur. Therefore, a key strategy is to simplify the problem such that it is tractable, yet realistic enough to produce a credible analysis.

Information gained from detailed process models at the subsystem level, natural analog studies, and laboratory and fieldwork are vital to carrying out the

performance assessment (Figure 3). To account for the uncertainty inherent in characterizing a large and complex system for such long periods, probabilistic simulations are used.

The CNWRA, and the NRC (the licensing authority) have developed a system of tools, referred to as performance assessment tools, for independent analysis of the repository performance[3]. NRC will use these to review a potential license application for the proposed repository. The main component, referred to as the Total-system Performance Assessment (TPA) code, provides quantitative understanding of the key factors controlling the degradation of the engineered system, the release of radionuclides from the repository, the transport of radionuclides through various environmental pathways, and possible human exposures. The TPA code was developed by a team of scientists and engineers with combined expertise in risk assessment, hydrology, materials science, mechanical engineering, rock mechanics, geology, volcanology, geochemistry, health physics, and computer science.

Conceptual Models

The following is a description of a scenario where an accidental release of high level waste produces a radiological dose to a typical member of an affected population. For this scenario it is assumed that the engineered barrier system fails, causing water infiltrating through the mountain to enter a failed waste package and dissolve radionuclides. As water flows through the unsaturated and saturated geologic media beneath the repository, it transports radionuclides to distant irrigation and drinking water wells.

Many factors affect the magnitude of these processes. The climate is likely to change with time and will likely increase the present-day infiltration rate over a 40,000-year period before it plateaus and the decreasing trend begins. Topography of the mountain, vegetation, soil cover thickness, presence of fractures, faults, lithophysal cavities (large voids that occur naturally within

rocks) and heterogeneities in the hydrogeology of the unsaturated zone will determine how much rainwater will infiltrate and move through the rocks. The water infiltrating into the mountain will get diverted around the drift, then around the waste package before entering small cracks in a compromised waste package and dissolving the spent nuclear fuel.

Heat generated from the decaying radioactive waste will lead to thermal-hydrological-chemical coupled processes affecting the environment for a period of time. During this time the drip shield and waste packages are susceptible to accelerated corrosion and the waste form is susceptible to accelerated dissolution.

Conduction, convection and radiation heat transfer will govern temperature and relative humidity variations at the repository near field, the drift wall, the waste package and the waste form. Water vapor created by above-boiling temperatures will likely move away from the waste package and perch above the near-field area after condensation, but will move back toward the repository in the fractures (known as refluxing) even when the waste package is still above the boiling point of water.

Seismicity in the region will induce rock falls in the drifts, or storage areas, which could cause a failure of the drip shield and waste package in the unbackfilled repository.

For release to occur, the waste package would have to fail and water would have to contact the radioactive waste. Waste packages and drip shields could fail because of hidden defects. Based on literature data, up to 1 percent of waste packages are estimated to have premature or juvenile failures due to manufacturing defects and emplacement accidents.

The chemical composition of the water will change under elevated temperatures and affect degradation of the engineered barrier, and thus the rate of radionuclide release. However, the most dominant and likely waste package failure will be from corrosion. Corrosion could occur in the presence of very little

water (humid-air corrosion) or in an aqueous environment (under a film of water). The size and shape of a breach caused by corrosion, the conditions in the near field environment and rate of water percolation into the drift, waste form (leaching) dissolution rate, and radionuclide solubility will determine the rate of aqueous releases of radionuclides from the waste package.

The progress of the release of radionuclides depends on the location of the breaches in a waste package. If breaches occur primarily on the upper half, the waste package will form a vessel similar to a bathtub in which the water must fill to the height of the breach before radionuclides spill out and are released. If breaches occur at the top and the bottom of the waste package, the water dripping on the waste form will release radionuclides without any accumulation. Radionuclides leaving the waste package could diffuse slowly through the medium surrounding the waste package or flow more rapidly through interconnected fractures.

There are other scenarios for the failure of the engineered system that are less likely but may have greater consequences. Those scenarios include:

- Displacement of a yet-unknown fault intersecting the repository, causing shearing of waste package and exposing radionuclides for release into the groundwater;
- Intrusion of magma that fails waste packages by a combination of high temperatures, corrosive conditions and large mechanical forces, exposing radionuclides for release to groundwater; and
- Extrusive volcanism that entrains the waste packages and ejects radioactive material with airborne volcanic ash. This phenomenon could allow the ash-spent fuel plume to move to great distances in the direction the wind is blowing.

The person who on average is most likely to receive a radionuclide dose would be a member of an existing farming community, referred to as the receptor group, located 12 miles from the repository where irrigation wells may be located. The receptor group could be exposed to radionuclides transported either

through groundwater, or through the atmosphere as a result of volcanism. The farm community receptor group would be comprised of persons who might drink contaminated water or use contaminated water for other residential purposes such as gardening; ingest contaminated, locally produced food products; are exposed to surface contamination, such as inhaling radioactively contaminated dust; and get direct exposure to radioactivity.

Dealing with Uncertainty

Because of the long time scales and because it is not possible to have perfect knowledge or understanding of all the components of the disposal system, estimates of repository performance can never be certain. However, decision-makers can still make well reasoned, risk-informed decisions regarding the safety of the proposed repository if the effects of uncertainties are evaluated.

Parameter and model uncertainties, spatial-temporal variabilities and design alternatives, if available, are considered so that a large number of potential scenarios can be considered.

Uncertainty and variability over a range of potential scenarios are propagated in the TPA tools by Latin Hypercube Sampling (LHS), a stratified Monte Carlo sampling approach. The uncertainties of key model input parameters are quantified by assigning probability distributions to them. Events that originate external to the repository (i.e., volcanism and faulting) could have high consequences but very low probability of occurrence. Such small probabilities often challenge probabilistic analyses. The TPA tools handle such shortcomings through specialized techniques.

Subsystem and System-level Results

The current climate at Yucca Mountain is arid; however, the climate will become moister and cooler over the next 40,000 to 60,000 years before returning to drier conditions around 90,000 years. Under the current climate, infiltration

through the mountain may be as much as 31 millimeters per year during the regulatory period, but could increase nearly 10 times during the wetter period that follows. Higher flow rates could potentially release a larger mass of radionuclides from the engineered subsystem to the natural system.

The peak repository temperature could reach an average of 165 degrees Celsius. Increased temperatures also increase the spent nuclear fuel dissolution rate, forms aggressive chemistry, alters water flow rates and increases the rate of corrosion of the waste package and the drip-shield.

If other mechanisms have not already failed the waste packages, corrosion could fail those over an estimated 38,000 -131,000 years, but that is significantly beyond the regulatory compliance period (i.e., 10,000 years).

A small fraction of the annual precipitation would infiltrate below the ground surface to the repository horizon and contact the waste package. A smaller fraction will contact the waste form and more than 99.99 percent of the water precipitating on Yucca Mountain corresponding to the repository footprint does not enter the waste packages.

Current calculations suggest that seismically induced rockfall or drift collapse will not fail waste packages over the entire regulatory period. On the average, some 0.37 percent of waste packages fail from fault displacement and 0.48 percent from intrusive igneous activity (magma flow in the drifts), but the probability of these conditional failures is low and the consequence is not high.

Groundwater release of radionuclides is therefore dominated by the initially defective failure of 0.5 percent of the waste packages, on the average, during the 10,000-year period. An estimated 0.045 percent of waste packages fail from extrusive igneous activity (volcanism), but even at this low level of failure and a very small probability of occurrence the risk (calculated as consequence times probability) is not negligible, as will be shown later, because the consequences of such a failure are high. Accounting for these disruptive events, 98.6 percent of the waste packages would remain intact for at least 10,000 years.

Radionuclide groundwater concentration arriving at the receptor location from initially defective waste package failure peaks anywhere between 3,700 - 32,000 years, while the peak concentration from corrosion occurs between 41,000 and 100,000 years. Radionuclides with a combination of high solubility, long half-life and large initial inventory exhibit the largest release rates. Nearly 300 Curies (Ci) of radionuclides are released on average from the engineered system, of which approximately 160 Ci arrive at the pumping well in 10,000 years. Although the unretarded radionuclides take an average of 640 years to travel in the groundwater aquifer, compared to 280 years in the unsaturated zone below the repository, the longer flow path, combined with greater retardation in alluvium, substantially delays transport of radionuclides to the pumping well.

Calculations to date for the undisturbed scenario show a peak dose risk to an average member of the receptor group of 2.1×10^{-4} millisievert (mSv) per year (0.021 millirem per year) in 10,000 years (see Figure 4). See side box for a table that provides a general guideline on the level of radiation received by the maximally exposed individual from various sources. For the 10,000-year regulatory period, three radionuclides are consistently the primary contributors to the peak risk from groundwater releases: iodine-129, technetium-99, and neptunium-237. In the disruptive scenario, volcanism could increase the peak dose risk during the 10,000-year period to 3.5×10^{-3} mSv/yr (0.35 millirem/yr).

Stylized calculations (calculated using constraints stipulated by the National Academy of Sciences) show that an inadvertent human intrusion, or intrusion as a result of exploration and development of natural resources or other purposes, could increase peak dose to 0.1 millirem/yr during the 10,000-year period.

Sensitivity Analysis Results

In addition to explaining how the number of waste packages failed or amount of radionuclides released from the engineered and natural systems with time affects the dose risk to the receptor, the CNWRA/NRC TPA tools also facilitate

the conduct of sensitivity (or uncertainty importance) analyses with parameters, repository system components and alternative conceptual models to determine the importance of uncertainties to repository performance.

The importance of such analyses cannot be over-emphasized because the subject matter experts have limited data to provide a reasonable process model (e.g., distribution functions to represent uncertainty in the system model). Calculations show that a 10-percent change to the mean of the distribution function provided by the subject matter experts could result in as much as a 150-percent change in the dose risk estimate.

Similarly, an example conceptual-model sensitivity analysis (using a magma-tunnel interaction model for waste package failure from volcanism) increased risk by one order of magnitude.

Repository component-level sensitivity analysis (Figure 5) showed that repository performance is relatively sensitive to the performance of the waste package, the unsaturated zone and the saturated zone.

The results of sensitivity analyses are used to determine how NRC should focus its resources in the high-level waste program and how pre-licensing interactions with the Department of Energy should be conducted.

Conclusions

The suite of probabilistic TPA tools developed at the CNWRA and NRC has helped the staff to independently evaluate the performance of the proposed repository at Yucca Mountain. In addition to obtaining an estimate of risk, these tools have been central to identifying influential repository components, models and parameters. These, in turn, have helped the NRC to identify the areas where additional resources may be needed to reduce uncertainties. The TPA tools have helped NRC in developing a risk-informed, performance-based regulation[4] and have aided the staff in refining their understanding of how various key features, processes, and events in an integrated system model influence risk estimates.

This knowledge will be vital to preparation for, and actual review of, the license application expected to be submitted by the Department of Energy in the near future.

As inherent to any performance assessment model, the results are based on numerous simplifying assumptions and the model uses only limited site-specific data. But the flexibility to conduct system-level analysis with different conceptual models, using data inside and outside the range of uncertainty dictated by limited data, has been found very effective.

REFERENCES

[1] DOE. Yucca Mountain Science and Engineering Report. DOE/RW.0539. Las Vegas, Nevada: DOE, Office of Civilian Radioactive Waste Management, Yucca Mountain Site Characterization Project. 2001.

[2] U.S. Nuclear Regulatory Commission. "High-level Radioactive Waste Management," Office of the Public Affairs: U.S. Nuclear Regulatory Commission, May 1984.

[3] Mohanty, S., R. Codell, J. Menchaca, R. Janetzke, M. Smith, P. LaPlante, M. Rahimi, and A. Lozano, System-Level Performance Assessment of the Proposed Repository at Yucca Mountain using the TPA Version 4.1 Code, CNWRA 2002-05, San Antonio TX (2002)

[4] U.S. Nuclear Regulatory Commission. "Disposal of High-Level Radioactive Wastes in a Proposed Geological Repository at Yucca Mountain, Nevada." Federal Register, Title 10–Energy, Chapter 1–NRC, Part 63. Washington, DC: U.S. Government Printing Office. 2002.

ACKNOWLEDGMENTS:

The Total-system Performance Assessment tools described in this article was developed by a multidisciplinary team of nearly 30 staff members from the Center for Nuclear Waste Regulatory Analyses, the Nuclear Regulatory Commission, and independent consultants. This article is based on the work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Material Safety and Safeguards, under Contract No. NRC-02-02-012. This article is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

Figure Captions for "Safety in the (Very) Long Run", Technology Today Summer 2003

Figure 1: The southern portion of Yucca Mountain, Nevada, looking southeast.

Figure 1 inset: The north entrance to the Department of Energy's exploratory study facility.

Figure 2. A conceptualization of the proposed repository at Yucca Mountain for system-level modeling. The magnification inset shows a waste package and drip shield within a tunnel of the repository.

Figure 3. Total-system Performance Assessment pyramid, showing the iterative process and stages of activity from data gathering to system-level assessment.

Figure 4. This hair diagram of groundwater radiation dose versus time represents 350 sample scenarios calculated for a 10,000-year simulation period, with graphed probabilities for the 75th and 95th percentiles and the expected value. At early times, doses from most scenarios are zero.

Figure 5. Example results from repository component sensitivity analysis using the TPA tools. The figure depicts cumulative additions of components to a hypothetical repository system. Each column represents a Monte Carlo analysis with one repository component added at a time. The left column represents the system with all components suppressed and the right column represents the base case in which all components are present.

Table 1: Radiation dose from common sources. Dose are expressed in millirems/year

Living in Las Vegas (i.e., background radiation):	89 mrem/yr
House construction (from stone, concrete, or masonry building)	7-25 mrem/yr
Eating, drinking, breathing (Potassium 40 in the Unites Sates)	25 mrem/yr
Medical x-ray (one chest x-ray)	10-39 mrem/yr
Lower gastrointestinal tract x-ray	500 mrem/yr
Round trip travel in a jet plane (For each 2500 miles, add 1 mrem)	2-5 mrem/yr
Cooking with natural gas	7 mrem/yr
U.S. annual average dose (includes Radon)	360 mrem/yr
Dose standard for Yucca Mountain (not to exceed)	15 mrem/yr

Fig1 (inset)

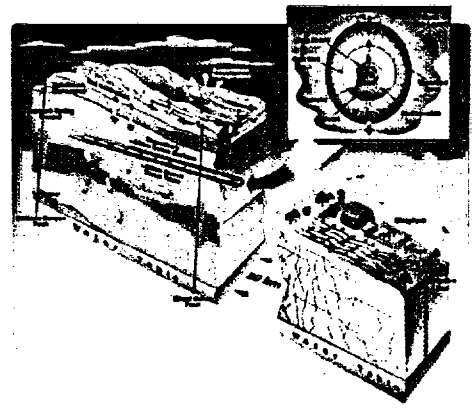


Fig 2

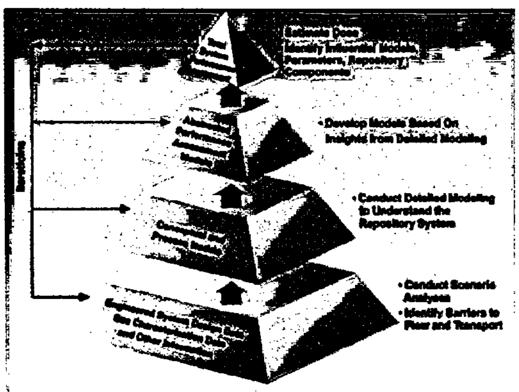


Fig. 3

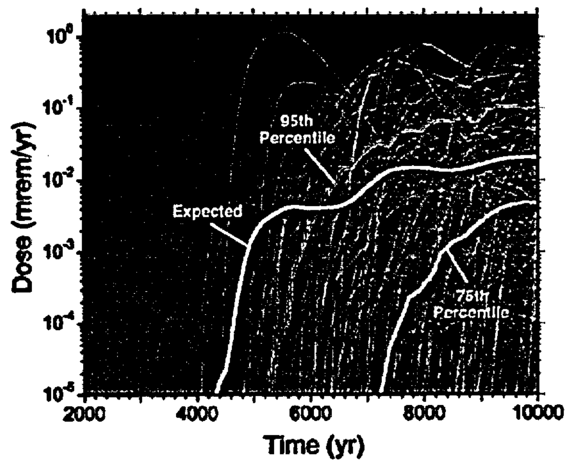
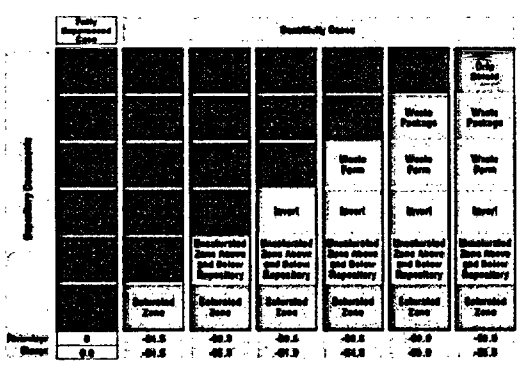


Fig.4



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