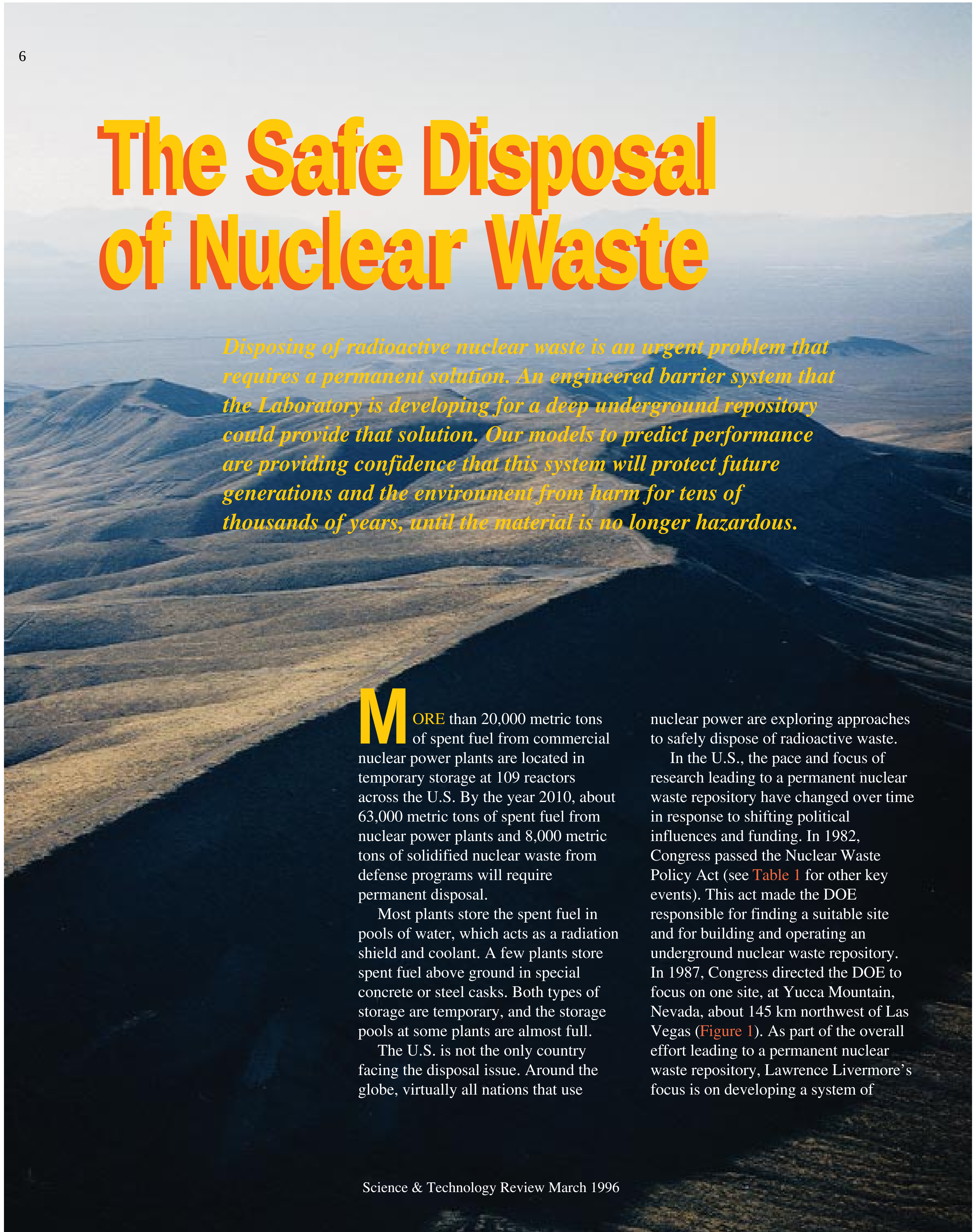


The Safe Disposal of Nuclear Waste

Disposing of radioactive nuclear waste is an urgent problem that requires a permanent solution. An engineered barrier system that the Laboratory is developing for a deep underground repository could provide that solution. Our models to predict performance are providing confidence that this system will protect future generations and the environment from harm for tens of thousands of years, until the material is no longer hazardous.

MORE than 20,000 metric tons of spent fuel from commercial nuclear power plants are located in temporary storage at 109 reactors across the U.S. By the year 2010, about 63,000 metric tons of spent fuel from nuclear power plants and 8,000 metric tons of solidified nuclear waste from defense programs will require permanent disposal.

Most plants store the spent fuel in pools of water, which acts as a radiation shield and coolant. A few plants store spent fuel above ground in special concrete or steel casks. Both types of storage are temporary, and the storage pools at some plants are almost full.

The U.S. is not the only country facing the disposal issue. Around the globe, virtually all nations that use nuclear power are exploring approaches to safely dispose of radioactive waste.

In the U.S., the pace and focus of research leading to a permanent nuclear waste repository have changed over time in response to shifting political influences and funding. In 1982, Congress passed the Nuclear Waste Policy Act (see Table 1 for other key events). This act made the DOE responsible for finding a suitable site and for building and operating an underground nuclear waste repository. In 1987, Congress directed the DOE to focus on one site, at Yucca Mountain, Nevada, about 145 km northwest of Las Vegas (Figure 1). As part of the overall effort leading to a permanent nuclear waste repository, Lawrence Livermore's focus is on developing a system of engineered barriers surrounded by natural ones to contain the highly radioactive waste.

Containment Objectives

Regardless of what site is eventually approved, a permanent repository for nuclear waste must comply with many federal, health, and safety regulations as well as extensive technical requirements. A key criterion is for essentially complete containment of nuclear waste for 300 to 1,000 years after permanent closure of the repository. Following that containment period, the release per year of any radionuclide (specific nuclear species) from the system cannot exceed 1 part in 100,000 of the radionuclide inventory present 1,000 years following closure. This rate cannot be exceeded for at least 10,000 years.

Such rigid expectations for a man-made system are unprecedented in history. For perspective, 10,000 years is the interval since the end of the last Ice Age, and the great pyramid of Cheops is less than half as old as that.

According to Environmental Protection Agency standards, the radioactive material remaining in nuclear waste at the end of 10,000 years would lead to health effects about the same in number as those associated with an unmined deposit of uranium ore of comparable size. Regulations state that a repository can cause no more than 1,000 health effects (namely cancer) to 10 billion people over 10,000 years.

The disposal problem is urgent, and we do not have much knowledge of how modern materials placed in a geological site and subjected to initially high temperatures and radiation will behave during thousands of years. Scientists obviously do not have a hundred centuries to validate a system. Thus, much of our development work at Livermore is based on predictive models and accelerated-age testing of materials and systems intended to delay the effects of water and other processes. Our overall task is essentially one of risk assessment.

The Laboratory's Role

Our current responsibility is focused on the engineered barrier system for an underground repository. This system includes the containers that will hold the waste and a complex series of interactions of the waste form and manmade waste package with the immediate or near-field environment.

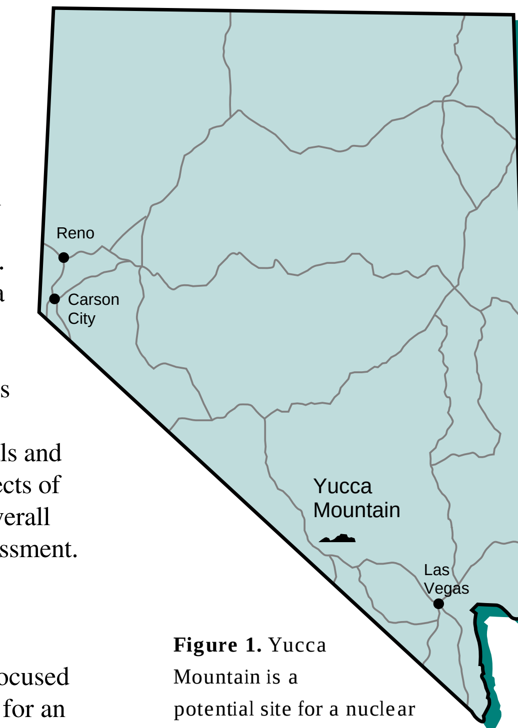


Figure 1. Yucca Mountain is a potential site for a nuclear waste repository. It is located in an uninhabited region of Nevada west of the Nevada Test Site.

Table 1. Summary of events leading to a nuclear waste repository. Some LLNL contributions are included for historical perspective.

1957	National Academy of Sciences recommends disposal in rock deep underground.
1963	Salt formations (vaults) studied as potential sites.
1975	Regional studies conducted in 36 states.
1977	LLNL begins research on issues related to disposal.
1979	Yucca Mountain identified as a highly promising repository site.
1982	LLNL begins to systematically survey candidate materials for the waste package.
1982	Congress passes the Nuclear Waste Policy Act.
1983	Nine potential disposal sites studied in six states.
1984	Three sites identified as leading candidates.
1987	Congress directs DOE to study only Yucca Mountain.
1989	Prototype field tests by LLNL and others at G-Tunnel near Yucca Mountain.
1995	Tunnel boring under way for Exploratory Studies Facility over 3 km within Yucca Mountain. Testing and licensing to continue for at least ten years.
1996	DOE considers a Waste Isolation Strategy emphasizing both engineered and natural barrier systems.
2010	Projected deposition of waste at a licensed repository.
2110	Performance period. The Nuclear Waste Policy Act stipulates that the drifts of the licensed repository remain accessible for at least 100 years so that waste may be reclaimed if necessary and performance of the containment systems can be monitored.

Our efforts date back to 1977 and now include the contributions of chemists, engineers, geologists, mathematicians, metallurgists, computer modelers, nuclear engineers, and physicists.

The system of manmade and geological barriers that will isolate nuclear waste can be envisioned as a set of concentric cylinders. Figure 2 shows a cross section of an underground repository with the waste, such as spent nuclear fuel, in the center. Moving outward, the following layers of engineered and natural barriers will help defend against the release of radioactivity:

- A robust waste package consisting of multiple containment barriers, each with a different but complementary purpose. We are studying various metal and alloy disposal containers that will surround either canisters or uncanistered designs.
- An engineered repository system of diffusion barriers, which may include packing materials around the waste package and backfill around the packing.
- The near-field environment, which can extend several hundred meters into the surrounding rock. Natural barriers, such as zeolitic rocks with high sorption capacity, can slow the migration of radionuclides.
- The far-field environment, which also can slow the migration of radionuclides. An arid climate with low precipitation, high evaporation, and no ground saturation will minimize the transport of radionuclides by water.

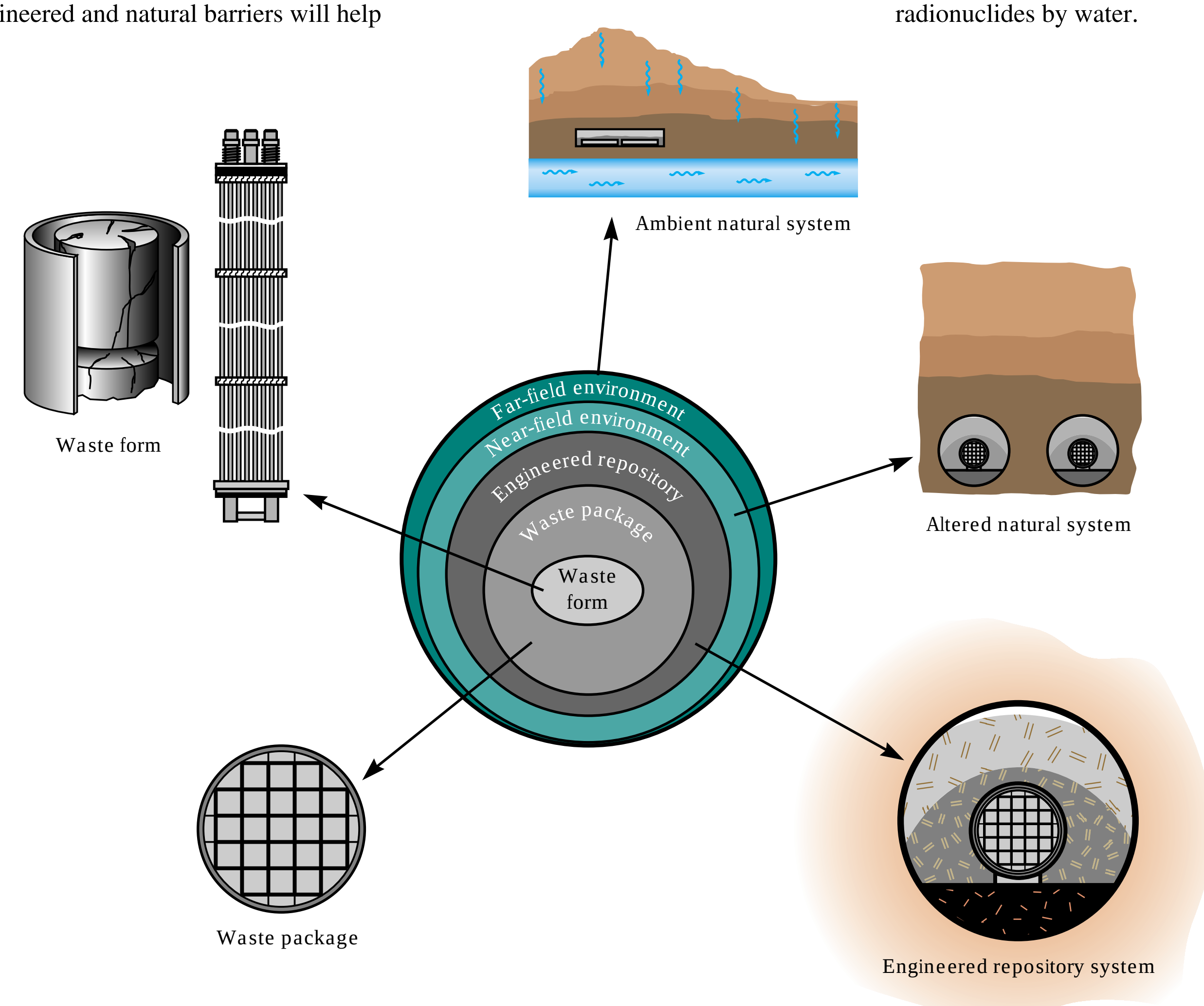


Figure 2. The performance of a nuclear waste repository depends on a system of manmade and natural barriers that will delay the release of radionuclides over thousands of years. LLNL's primary responsibilities include selecting materials for the waste package and assessing interactions with the near-field environment extending several hundred meters into the rock.

Our tasks can be broken down into four major areas: characterizing the waste itself, evaluating materials for the waste package, defining the near-field environment, and analyzing the long-term performance of barrier systems. According to project leader Bill Clarke, LLNL researchers have made tremendous progress on all fronts.

Why Water Is Important

Water is a major concern because of possible corrosion of waste packages and because water can dissolve and transport radionuclides. An important issue is how the heat generated by nuclear waste will mobilize any available water in the vicinity and where that water will go.

Elevated rock temperatures can be advantageous because heat acts as a barrier in a repository. Heat dries nearby rock and keeps moisture away. (See the box at the right.) Locating a repository well above the water table will further minimize container corrosion, leaching, and transport of radionuclides. The series of engineered barriers combined with natural barriers shown in Figure 2 will further delay interactions with water. Through the cumulative effects of these and other factors, we can delay the transport of radionuclides by water for perhaps tens of thousands of years according to our current models. During that time span, the radioactivity of the waste will decay to low levels—to about one-ten-thousandth of the original levels of radioactivity, or less.

Scientists elsewhere are studying the potential for earthquakes, fault movement, and volcanic activity; the effects of possible climate changes; and the potential for unacceptable environmental, social, economic, or transportation-related risks. Licensing of a repository depends on the outcome of these and many other studies.

What Is Repository Waste?

Nearly 90% of the waste at a permanent repository will be spent fuel from nuclear reactors. Reactor fuel for nuclear power plants consists of solid pellets of enriched uranium oxide sealed in cladding of corrosion- and heat-resistant zirconium alloy. The tubes are bundled to form a nuclear fuel assembly, and the fuel is used for 3 to 5 years, until it no longer efficiently generates heat. Spent fuel assemblies weigh 230 to 550 kg, depending on the type of reactor from which they come. The inventory consists of fission products with a half-life that is generally less than 100 years and actinides with half-lives of many thousands of years. A permanent repository will store the fuel assemblies and associated hardware.

About 10 to 15% of the repository waste will be high-level waste generated by defense programs. This waste is a mixture of byproducts containing highly radioactive fission products, traces of uranium and plutonium, and other transuranic elements. Before permanent disposal, this waste will be vitrified, that is, converted into a borosilicate glass.

A Way to Keep Waste Dry with Its Own Heat

At the November 1995 annual meeting of the Materials Research Society in Boston, Lawrence Livermore scientists unveiled a promising approach for storing nuclear waste containers at a potential national repository at Yucca Mountain, Nevada.* The system would use the heat given off by waste storage containers to produce a dry environment that could keep thousands of tons of nuclear waste safely stored for tens of thousands of years.

Using computer models, Laboratory scientists examined a plan being considered that would place large cylinders, each containing 12 tons of waste, in horizontal tunnels 240 to 300 meters within Yucca Mountain. Located 145 kilometers northwest of Las Vegas, the mountain is under study by DOE to determine its suitability as a permanent repository site.

Based on their studies, the Livermore researchers developed a "localized dryout" design approach that provides two key recommendations: (1) position waste containers close together to generate enough heat to lower the relative humidity at the surface of the containers, and (2) surround the waste containers with sand—or layers of gravel and sand—to help prevent water from dripping onto the containers and to increase the temperature difference between containers and the surrounding rock walls. The latter technique would further reduce humidity at the surface of the containers.

The Lab scientists also recommended that tunnels be spaced as much as 45 to 90 meters from one another to mitigate potential water drainage problems.

Laboratory hydrologist Thomas Buscheck said he and his colleagues are looking forward to testing their "barrier concepts" in experiments being planned by DOE in 1996. Tests would place heaters that mimic waste containers into tunnels in Yucca Mountain to see how well Livermore computer codes predict actual conditions.

* Thomas Buscheck, *et al., Localized Dry-Out: An Approach for Managing the Thermal–Hydrological Effects of Decay Heat at Yucca Mountain*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-121332 (1995).

Modeling the Waste Forms

Except for a few gaseous radionuclides, radioactivity would potentially be released from an underground repository when groundwater comes into contact with the waste. Thus, our experimental work on characterizing the waste forms is largely aimed at determining the potential for the release of waste in groundwater. Because we cannot always measure all important variables experimentally, we are using models to predict the thermal, structural, chemical, and nuclear responses of the waste forms over time. These models allow us to extrapolate the results of laboratory experiments to the very long times relevant to a repository.[1]

Vitrified Waste

Glass is highly durable if kept dry. However, if water contacts the vitrified wastes in a repository, the glass can slowly transform into a composition similar to minerals found in soils.

We have been testing glass durability for almost 10 years under a wide variety of conditions that mimic the anticipated repository environment. At the temperatures we expect, our experiments lasting a few months show that 0.001 to 0.1 grams of glass dissolve per square meter of glass surface area per day. At that rate, the glass would last for several thousand years. Longer-term experiments together with computer models based on glass and water reactions will allow us to more confidently extrapolate reaction rates to the lifetime of a repository.

We still need to improve our models to account for other interactions among glass, water, and minerals. For example, magnesium, a common geologic element, can slow the dissolution of glass in water by a factor of at least 10. This type of information can be used to enhance the durability of the glass waste forms.

Spent Nuclear Fuel

To characterize how the spent fuel, the predominant waste, will behave in the repository, we have focused on determining rates of dissolution and other processes that affect the release of radionuclides. These processes include oxidation of uranium oxide fuel, degradation and failure of the zirconium alloy cladding, and the release of radionuclides from cladding and assembly hardware. From the results of our ongoing experiments, we have developed models to predict these processes over a broad range of variables, including water chemistry, fuel-pellet size, grain boundaries, temperature, radionuclide inventory, and a host of other factors. As with our models for vitrified waste, we are trying to predict the long-term performance of the total repository system. The dual approach of experiments and models addresses both regulatory and safety issues and is the best way to design a system that must perform for thousands of years. The same type of approach can be used to address complex problems associated with the safe disposal of many other toxic substances.

Packaging Waste

Three concepts[2] have been selected for the waste packages: both uncanistered and multipurpose canister waste packages for spent nuclear fuel and a smaller high-level waste package for vitrified waste.

A design for an uncanistered spent fuel waste package is shown in Figure 3a. A basket assembly, which is a large cylinder with partitions, provides structural support for about 20 spent fuel packages and helps to control criticality and heat. The basket is mounted inside a multibarrier metal container. Our concept for this container is to use two different layers of metal, each of which performs a different function in the oxidizing geological environment. By selecting diverse barriers that provide different types of protection, we can minimize the possibility of failure by any single mechanism.

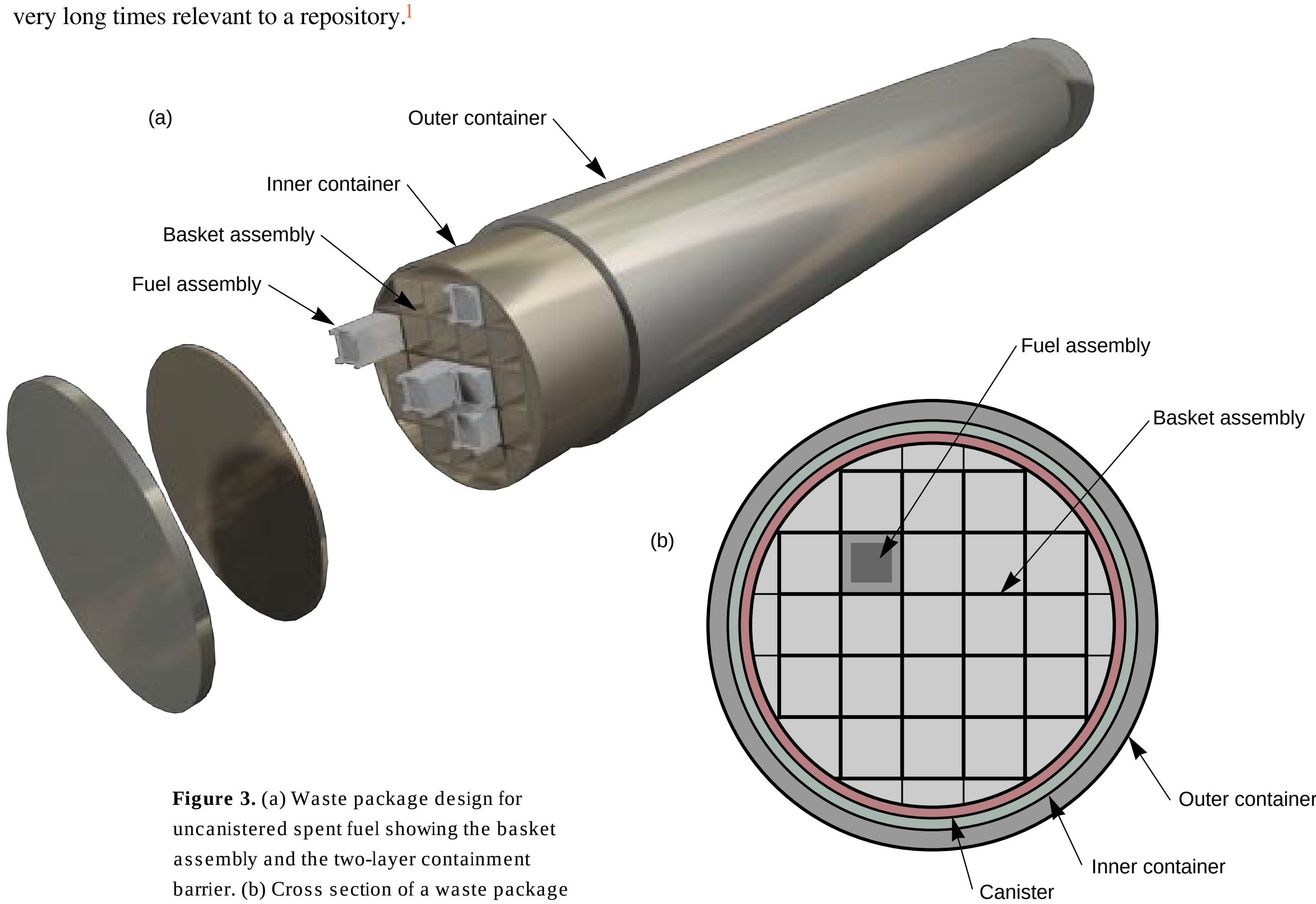


Figure 3. (a) Waste package design for uncanistered spent fuel showing the basket assembly and the two-layer containment barrier. (b) Cross section of a waste package containing a multipurpose canister used for transportation, storage, and disposal.

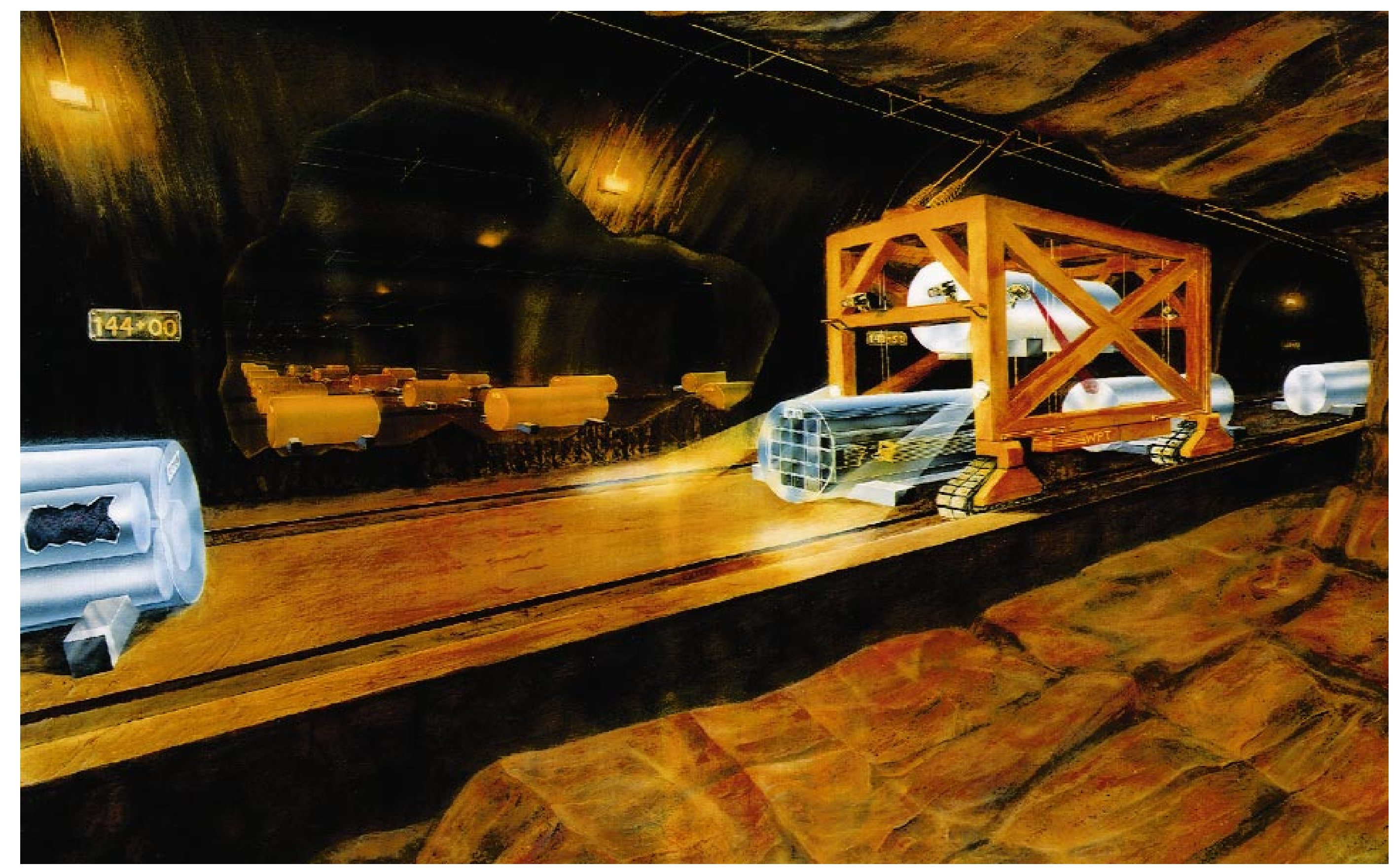


Figure 4. Waste packages will be placed on rails in horizontal tunnels, called drifts, about 300 meters underground. The tunnels would remain open for 100 years to permit monitoring and to allow for retrieval if a problem is discovered or if some use is found for the spent fuel. After that period, the tunnels would be filled and sealed.

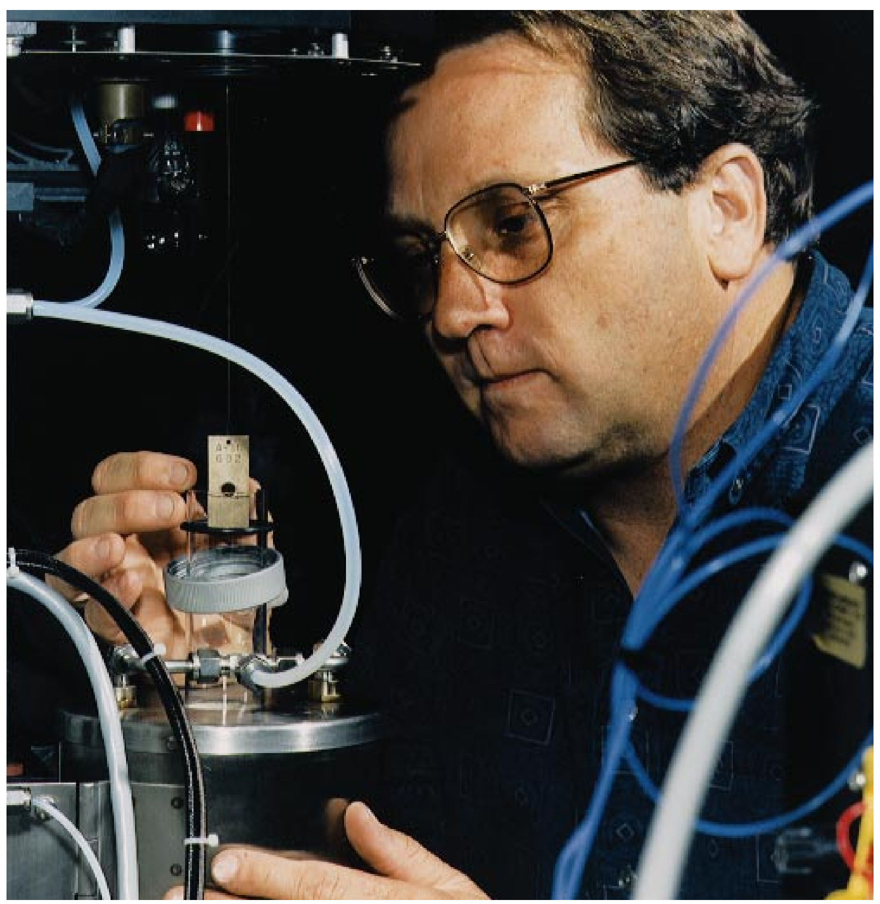


Figure 5. A thermogravimetric analyzer tests for oxidation of metals exposed to environments of 50 to 90% relative humidity. Livermore researcher John Estill adjusts the equipment for tests that can run 1 to 30 days at temperatures of 50 to 250°C.

A 2-cm-thick inner layer of highly corrosion-resistant material will contain the radionuclides. A 10-cm-thick outer layer of less expensive corrosion-allowance material will protect the inner layer and attenuate gamma rays. The outer layer is a sacrificial barrier, similar to the lining of tin that protects the steel of a tin can. Because this layer is thick and corrodes at a very low rate when the waste is at high temperature, it protects the corrosion-resistant layer for a prolonged period.

A design for the multipurpose canister waste package is shown in Figure 3b. This package is similar to the one just described except that it adds a large cylindrical canister between the basket assembly and the outer multibarrier container. These multipurpose canisters, thousands of which will be filled and sealed at reactor sites, will be designed to be safe for both transportation and disposal.

At the repository, an unopened multipurpose canister will be inserted into our disposal containers to make up the complete waste packages (Figure 4). Filler material may be placed in the space around fuel rods to help exclude water, transfer heat, control criticality, and provide chemical buffering. Packing and backfill may also be used outside, under, or near the waste packages. This material can help to restrict water access or to sorb radionuclides. The engineered barrier system includes all of the above components.

For the smaller amounts of high-level waste generated by defense programs, three or four canisters containing borosilicate glass waste will be inserted into a multibarrier metal container.

The materials we are evaluating for structural containers are intended to provide substantially complete containment of nuclear waste between 300 and 1,000 years after the repository is closed. Of all the properties relevant to the waste package materials, the most important is corrosion behavior.

Testing, Selecting Materials

At Lawrence Livermore, we are testing materials for the spent-fuel basket assemblies, the multilayer containers, and filler. Focusing mostly on the containers, we evaluated 41 materials, including nearly all major families of engineered alloys, and have narrowed the list of candidates using criteria such as corrosion resistance,

mechanical performance, cost, and ease of fabrication.[3]

Many considerations govern the tests we perform, the models we are developing, and the materials finally selected. One of the most important factors is that a repository environment starts with very high temperatures and dry conditions, and it becomes cooler (about 100°C after 1,000 years) and more humid over time. Depending on the metal and its temperature, corrosion can become significant at a relative humidity above about 60%. Some of our tests, such as thermogravimetric studies (Figure 5), are designed to identify this critical transition point in candidate metals.

For a container made of two different metal layers, we want to select materials that will interact beneficially and age differently as the repository environment changes from drier to moister. Other variables that we design into our tests are based on the following facts:

- Several different types of corrosion are possible, including localized pitting, crevice corrosion, and stress corrosion cracking.
- The contents of the approximately 12,000 waste canisters will differ in terms of their radiation, chemistry, and temperature. Gamma radiation affects corrosion mechanisms as do other variables arising from the waste form.
- The effect of welds and mechanical stresses on metal must be assessed along with the shapes and compositions of small metal parts (Figure 6) and the configuration of the containment barriers.
- Other repository structures, such as concrete and grouts, interact with the metal containers.
- Microbes can drastically change the chemical environment. In acidic conditions, microbes can cause high corrosion rates in metal at temperatures of 30 to 120°C. This is a relatively new area of study.

In tests on a laboratory scale, we intentionally accelerate the aging and deterioration of candidate metals so we can extrapolate results to thousands of years. For the first time, our new Integrated Corrosion Facility (see the box on p. 16) allows us to run tests for five years or longer. We are also developing modeling tools to help predict localized corrosion and other processes.

Primary candidate materials being studied are high-performance nickel and titanium alloys for the inner containment barrier and carbon steel for the outer, sacrificial containment barrier.

Nuances in alloy composition are important. Nickel-rich stainless alloys are known as "super stainless steels" in which increased nickel content confers added corrosion resistance. Alloy 825 is a nickel–iron–chromium alloy (40 to 60% nickel) developed for equipment to handle sulfuric acid. It is a strong candidate for the inner barrier with excellent corrosion and oxidation resistance and desirable mechanical properties. However, it may have less resistance to crevice attack than some alternative alloys with more molybdenum content. Titanium-based alloys (1% or less of alloying elements) have excellent corrosion resistance to

Figure 6. Some of the thousands of metal alloy samples we are subjecting to stress, heat, water, and chemicals to determine their long-term performance: penny shapes of copper for electrochemical disks, stainless steel U bends for stress–corrosion tests, a ring of plasma-sprayed carbon steel, and large U bends of pure copper and copper–nickel for aggressive tests of welded samples.

Table 2. Near-field environment studies and accomplishments by LLNL.

LLNL focus areas
- Chemistry of fluids that can contact waste and containers.
- Waste form and other engineered barrier system components.
- Mechanical loading imposed on containers and other components.
- Thermal environment.
- Formation of colloids.
- Potential biological activity and interactions.
- Electrical potential interactions.
- Transport and retardation mechanisms.

Computer models
- LLNL-developed EQ3/6 for chemistry of rocks and water.
- V-TOUGH and NUFT codes for hydrology and thermohydrology.
- Geomechanical codes for fracturing in rock.

Laboratory tests
- Geochemical tests for rock and water interactions.
- Hydrologic and geomechanical properties of rock at elevated temperatures.
- Drying and rewetting of fractures.
- Breakdown of organics, such as diesel fuels.
- Long-term effects of microbes on concrete.

Field tests
- Climax Mine underground tests (early 1980s).
- G-Tunnel test at Nevada Test Site (October 1990).
- Tests on a large block of tuff.
- Tests on analogous formations around the world.
- Exploratory Studies Facility (boring is ahead of schedule for this 5-mile loop tunnel under Yucca Mountain).

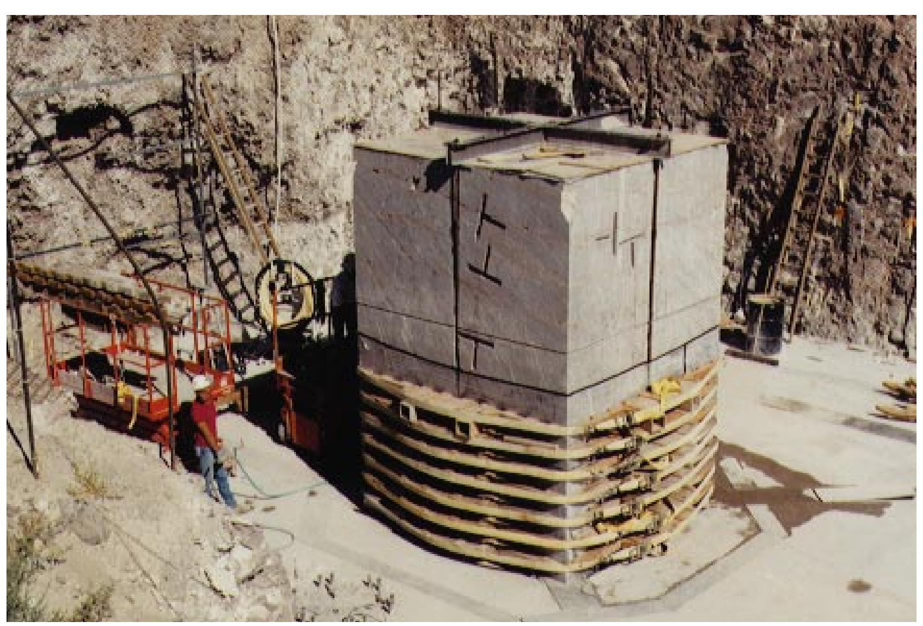


Figure 7. We are preparing this 3- ¥ 3- ¥ 4.5-m rock for our near-field studies. The outer straps (shown partially in place) will help keep the rock from fracturing during tests and provide insulation. We are placing heaters on the exterior of the rock and in five boreholes within the rock. Monitoring instruments capable of gathering 1,000 channels of data are also being placed in boreholes in the rock.

oxidizing environments and microbial attack, low density, and high strength, but they can lose resistance in reducing acids and in crevices. Carbon steel for the outer barrier is an excellent choice in hot, dry conditions, but we must take into account that its corrosion rate becomes higher in wet conditions.

Trade-offs like these together with issues of cost and other possible failure mechanisms will continue to direct our research and the final choice of materials. By studying both expected and worst-case conditions that are possible in a repository, we can identify the best materials and designs to withstand those conditions. Testing and modeling materials are ongoing activities that yield greater confidence over time. As an added precaution, materials tests will continue even after a repository is built because the waste packages will be retrievable for many years.

Near-Field Environment

The immediate, or near-field, environment surrounding the waste will change over thousands of years as heat and radioactivity interact with water, rock, and introduced materials. The altered environment will, in turn, affect the waste packages.

Our near-field studies include the disciplines geochemistry, geohydrology, hydrothermal interactions, geomechanics, manmade materials, field tests, and modeling. We have published a two-volume *Preliminary Near-Field Environmental Report* that summarizes our extensive studies.[4] Table 2 lists many of our accomplishments.

A good example of our current work is the tests we plan to conduct on a heavily instrumented, room-size block of rock (Figure 7) adjacent to the proposed Yucca Mountain site. We are placing heaters in five boreholes within the rock and surrounding the sides with

additional heaters. Instruments in this rock will gather 1,000 channels of data on moisture, temperature, geochemistry, water chemistry, corrosion of metal samples, gas pressure and vapor, acoustics, deformation, and rock stresses. After collecting data for about a year and a half, we will take the rock apart to gather more information.

The Exploratory Studies Facility, now being constructed, will provide us with on-site laboratories deep within Yucca Mountain in 1996. We plan an extensive series of tests that will give us much more specific data on the hydrology and geochemistry of the actual environment. Such data will allow us to develop more accurate computer models of processes affecting the repository.

Putting It All Together

Ultimately, we must have very high confidence in the long-term safety of the potential repository. Figure 8 is a broad view of how we are analyzing each aspect of the engineered barrier system and near-field environment to come up with the required measure of total system performance needed for licensing. Performance analysis of the waste package design and repository drives our entire program and will determine its success.

To more readily visualize the many elements making up our analysis, Figure 8 represents the factors leading to total system performance as a pyramid. At the base of the pyramid is our detailed work on the waste form and containers and on the waste package environment, which is being analyzed by means of our near-field studies.

In the middle of the pyramid are the models we are developing to describe the long-term behavior of the engineered barrier system and the environment in which it will function. Some of our models are computer-based, while others are mathematical or analytical. This work uses data from other models, such as those in geochemistry or hydrology, to determine how processes will interact over thousands of years.

Toward the top of the pyramid are the subsystem models describing performance of the engineered barrier system. For example, the PANDORA model is a detailed time evolution of a single waste package. We have also developed the Yucca Mountain Integrated Model, which combines information on the engineered barrier system with that on the near-field environment. This model tells us which trends are most significant and what data are essential for predicting repository performance. We can use this information to plan additional tests and to further analyze designs. Eventually, our subsystem models can be used to develop the ultimate model of the entire repository with all elements included, that is, to assess total performance.

The models in Figure 8 are representations of experiments. To test our representations and verify that a code correctly represents real processes, we will continue to conduct laboratory and field tests. For example, we can couple the release of radionuclides and their potential movement through heated rock to compare test data with a model's predictions. When

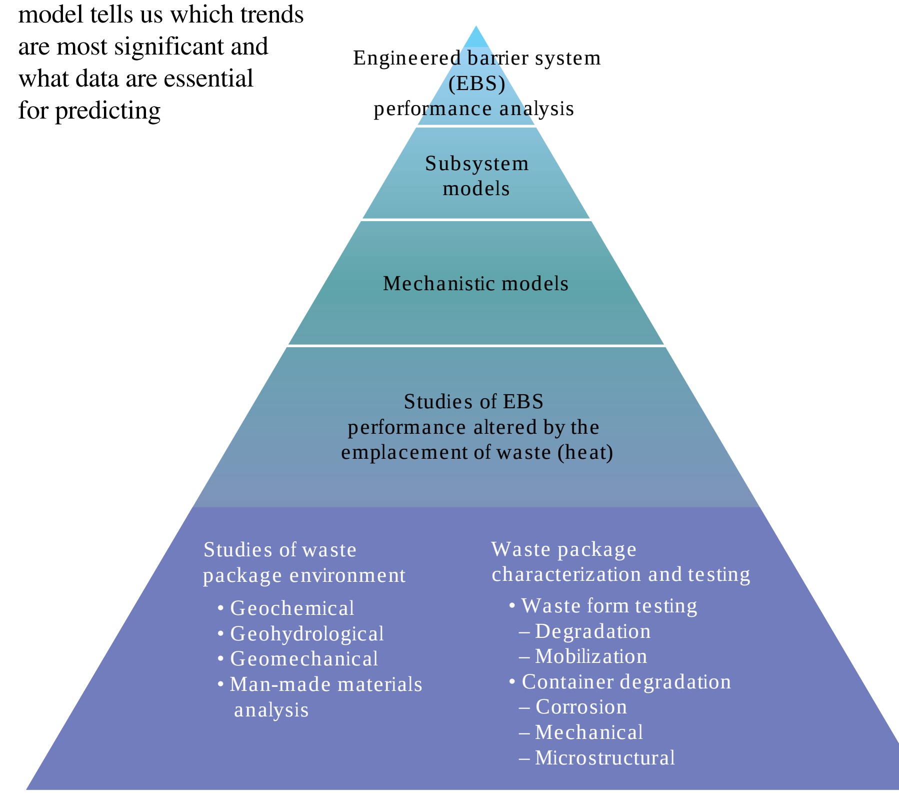


Figure 8. Summary of LLNL's role in repository research. Starting with the waste package (bottom right) and our near-field studies (bottom left), we are developing models for evaluating the total performance (top) of an engineered barrier system.

the Exploratory Studies Facility is completed at Yucca Mountain, we will proceed with more extensive integrated tests to validate our models and methods.

Key Words: engineered barrier system (EBS); high-level radioactive waste; spent fuel; Yucca Mountain Project.

References

1. R. B. Stout and H. R. Leider, *Preliminary Waste Form Characteristics Report*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-108314 (Rev. 1) (1994).
2. *Initial Summary Report for Repository/Waste Package Advanced Conceptual Design*, TRW Environmental Safety Systems, Document No. 00000000-01717-5705-00015, Rev. 1 (August 29, 1994).
3. R. A. Van Konynenburg *et al.*, *Engineered Materials Characterization Report for the Yucca Mountain Site Characterization Project,* Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-119564 (Vols. 1, 2, and 3) (1995).
4. D. G. Wilder, *Preliminary Near-Field Environmental Report, Volume I: Technical Bases for EBS Design; Volume II: Scientific Overview of Near-Field Environment and Phenomena*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-LR-107476 (Vols. 1 and 2) (1993).

For further information contact Bill Clarke (510) 423-4571 (clarke1@llnl.gov).

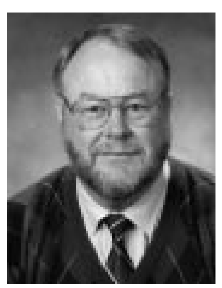
Integrated Corrosion Facility

To project effects on candidate metals over a hundred centuries, we need to do laboratory corrosion testing for as long as possible, several years at least. Our new corrosion-testing laboratory at Livermore (Building 435) allows us to investigate modes of degradation in candidate materials for the required times.

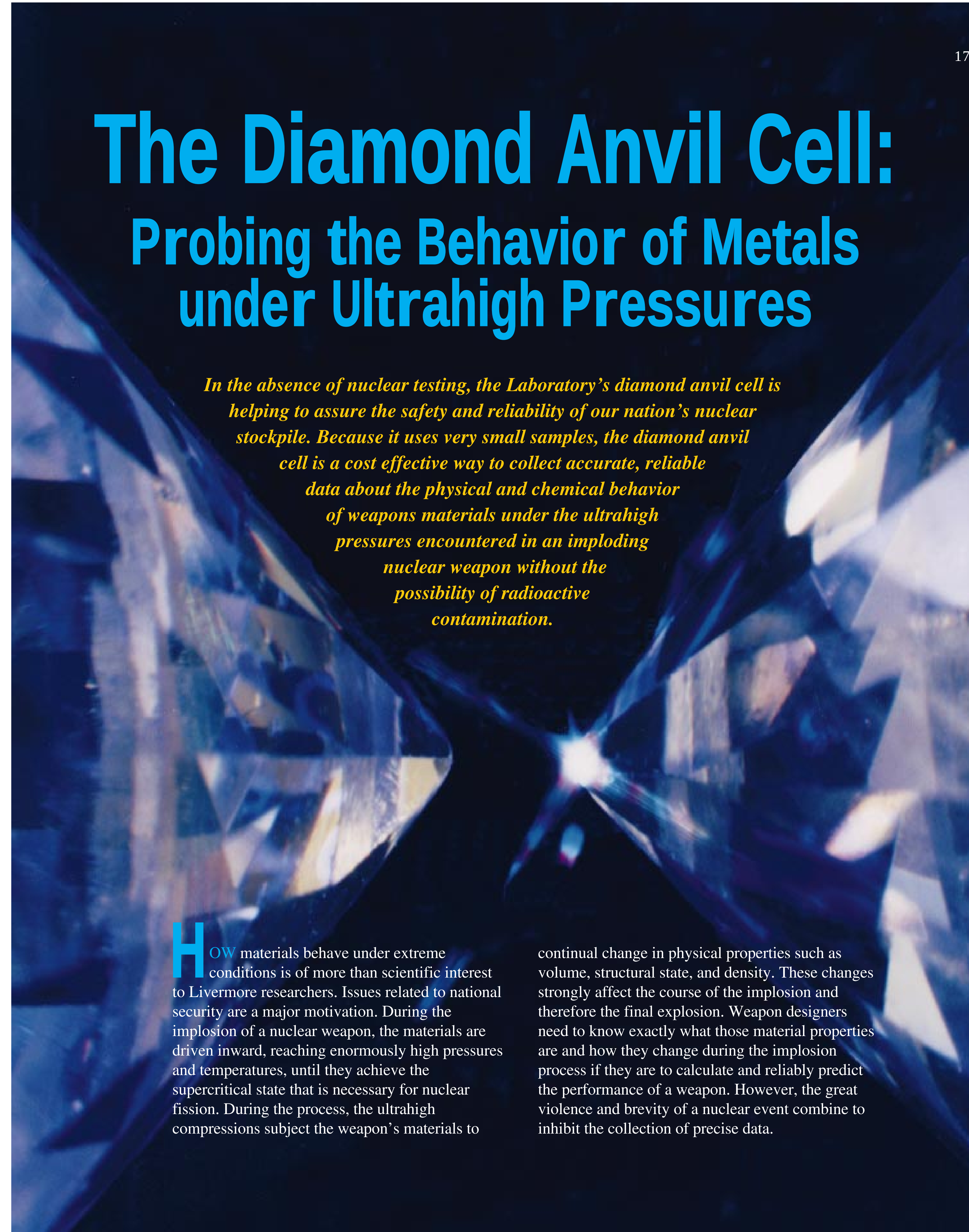
This facility contains several dozen large tanks approximately 1 meter square and 2 meters high in which we can simulate conditions that are possible at a repository. Test solutions are varied and controlled for temperature, pH (acidity), solution chemistry, and many other variables. Metal samples are immersed in the aqueous solutions or subjected to the vapor phase to study generalized, localized, and stress-assisted corrosion.

Some samples will be exposed for five years or more, still just a fraction of the time the material must last in the repository. To measure changes in corrosion rates, we will remove samples of candidate materials at six-month intervals for kinetic and mechanistic analysis. Some of our exposure conditions, such as electrochemical polarization, intentionally accelerate the corrosion process. For different exposure conditions, we use computer models to project corrosion effects to much longer times. Thus, the effects we assess can correspond to the vastly longer exposure times in an underground repository.

About the Scientist



WILLIS L. CLARKE received his B.S. in metallurgical engineering from the University of Nevada, Reno, in 1960. He joined the Laboratory's Chemistry and Materials Science Department in 1989 after holding several research and managerial posts, including lengthy service as principal engineer at the Vallecitos Nuclear Center at Pleasanton, California. Since 1991, he has been project leader at Lawrence Livermore for the Yucca Mountain Site Characterization Project, managing a staff of from 40 to 80 researchers focusing on the design of an engineered barrier system for a permanent nuclear waste repository. He has published more than 80 articles on materials performance, including the effects of radiation, oxidation, and corrosion on metals and alloys.



The Diamond Anvil Cell:

Probing the Behavior of Metals under Ultrahigh Pressures

In the absence of nuclear testing, the Laboratory's diamond anvil cell is helping to assure the safety and reliability of our nation's nuclear stockpile. Because it uses very small samples, the diamond anvil cell is a cost effective way to collect accurate, reliable data about the physical and chemical behavior of weapons materials under the ultrahigh pressures encountered in an imploding nuclear weapon without the possibility of radioactive contamination.

HOW materials behave under extreme conditions is of more than scientific interest to Livermore researchers. Issues related to national security are a major motivation. During the implosion of a nuclear weapon, the materials are driven inward, reaching enormously high pressures and temperatures, until they achieve the supercritical state that is necessary for nuclear fission. During the process, the ultrahigh compressions subject the weapon's materials to continual change in physical properties such as volume, structural state, and density. These changes strongly affect the course of the implosion and therefore the final explosion. Weapon designers need to know exactly what those material properties are and how they change during the implosion process if they are to calculate and reliably predict the performance of a weapon. However, the great violence and brevity of a nuclear event combine to inhibit the collection of precise data.