The combination of Yucca Mountain's natural features and technology-based engineered components supports a defense-in-depth approach and achieves the repository's objectives of isolating high-level waste and minimizing the amount of radioactive material that can migrate from the facility, thus protecting the human environment.

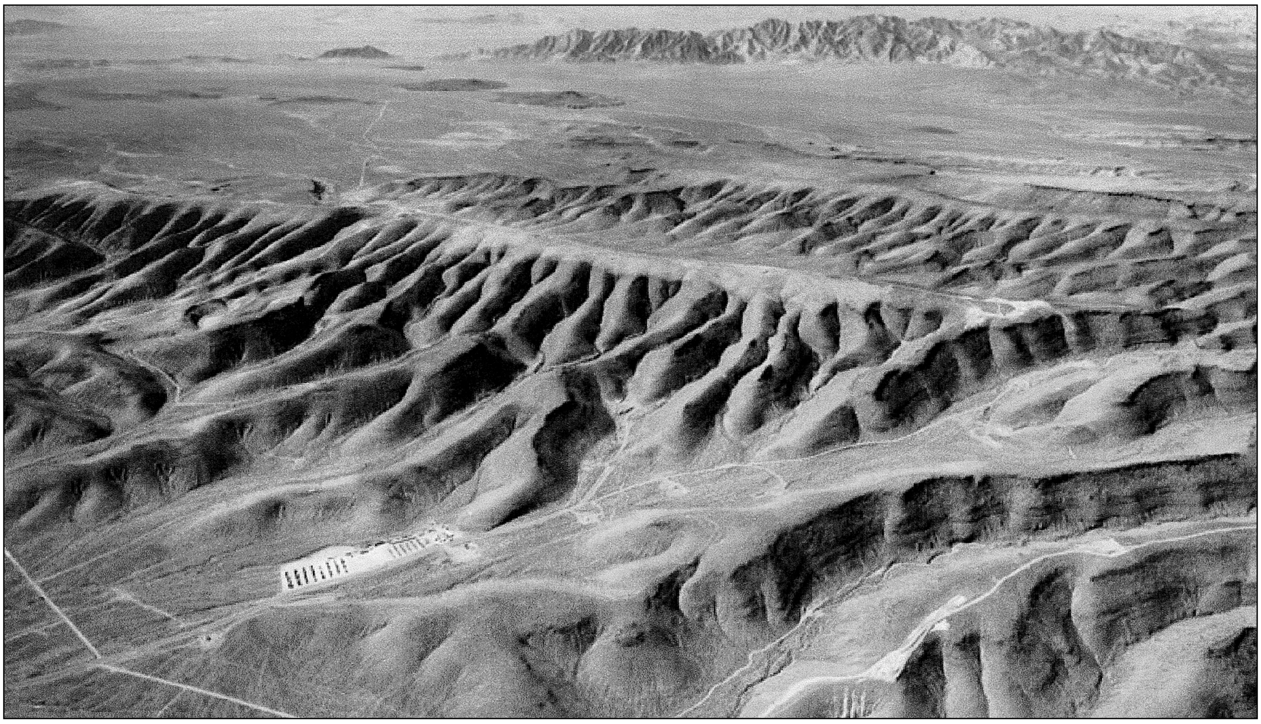

Fig. 1. Overhead view of the Yucca Mountain ridge.

The Evolution of Spent-Fuel Waste Packages

Designing the Means to Permanently Dispose of U.S. High-Level Nuclear Waste

By Hugh Benton and Judy Connell

Years of research and thousands of experiments have gone into solving the problem of what to do with the nuclear waste generated by the U.S. civilian and government nuclear programs. The commercial nuclear power industry and the U.S. Department of Energy's Environmental Management Program both assume the availability of a permanent disposal facility. Already, nearly 40 000 metric tons of spent nuclear fuel is being stored temporarily at more than 70 locations across the country, and this amount could more than double in the next 35 years. Furthermore, by 2035 the United States will have to dispose of approximately 2500 MT of spent fuel from defense-related reactors (including those from the U.S. Navy's nuclear-powered ships and submarines) and research reactors, in addition to the 8000 MT of solidified material and the 100 million gallons of liquid waste currently in storage at three major DOE sites in Idaho, South Carolina, and Washington.

Right now, Yucca Mountain is the only site being evaluated as a permanent disposal facility (see Fig. 1). It is limited by law to accommodate 70 000 MT of heavy metal—although its capacity could be increased to 118 000 MT should repository requirements and legal constraints change. Approximately 90 percent (63 000

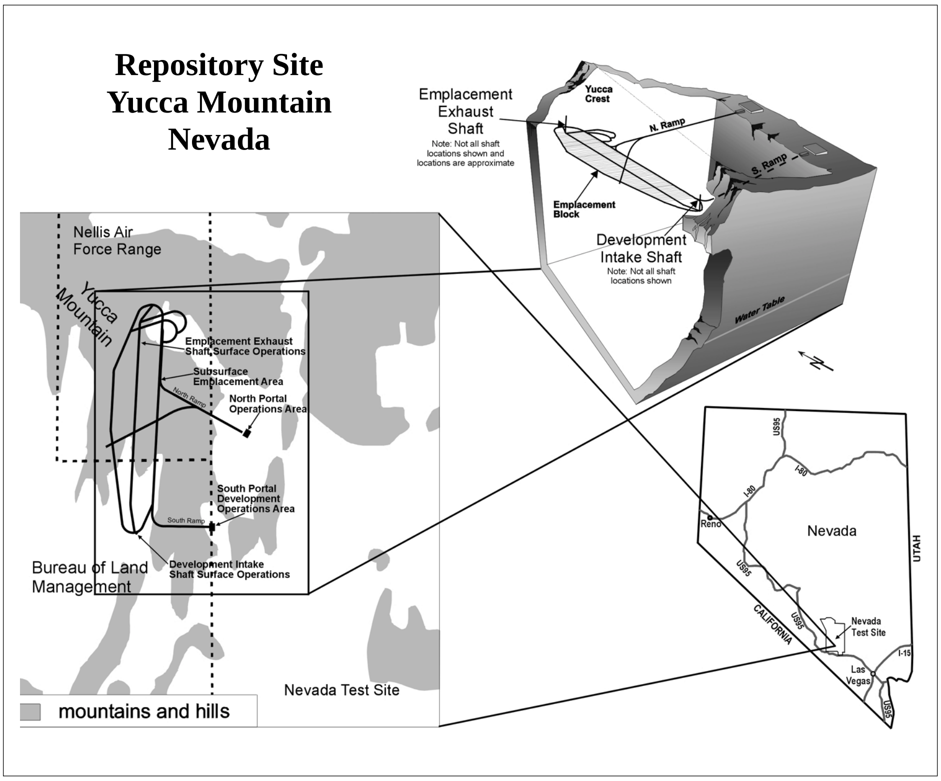

Fig. 2. Yucca Mountain is about 100 miles northwest of Las Vegas, on land that is adjacent to the Nevada Test Site and owned by the federal government. The area has a desert-like climate and gets about 7 inches of precipitation a year.

Yucca Mountain is slated by law to accommodate 70 000 MT of heavy metal—although its capacity could be increased to 118 000 MT should repository requirements and legal constraints change.

MT) of this material comes from commercial spent fuel; the rest will come from DOE-owned HLW. The DOE's inventory comprises more than 250 types of spent nuclear fuel, including aluminum-clad fuel, as well as vitrified wastes from reprocessing and immobilized plutonium.

Proposing a Solution

In 1982, Congress set a national policy of deep geological disposal for highly radioactive waste through the Nuclear Waste Policy Act, which made the DOE responsible for identifying a site and building and operating a monitored geologic repository. In 1983, the DOE identified nine locations in six states for consideration; three were subsequently selected for intensive characterization: Hanford, Wash.; Deaf Smith County, Tex.; and Yucca Mountain, Nev. In 1987, Congress directed the DOE to study Yucca Mountain—an area of uninhabited desert in Nye County on federal land in southern Nevada, about 100 miles northwest of Las Vegas (see Fig. 2). This decision reduced the total costs of the investigations by concentrating on a single site that appeared suitable.

Since then, scientists have studied Yucca Mountain to test and verify its natural ability for isolating nuclear waste thousands of years. At the same time, technology has been, and is continuing to be, developed that supplements the site's natural systems to confine the waste. The combination of the mountain's natural features (the natural barrier system) and technology-based engineered components (the engineered barrier system) supports a defense-in-depth approach and achieves the repository's objectives: isolate the waste and minimize the amount of radioactive material that can migrate from the facility, thus protecting the human environment.

Should the repository at Yucca Mountain be built, it will be the only such facility in the world to store the waste *above* the water table—in fact, more than 1000 feet above the saturated zone yet still 1000 ft below the surface of the mountain (see Fig. 3). This unique placement of the waste is attributable to the site's geological, hydrological, climatological, and geochemical subsystems. Characterization studies have shown that the repository will not flood, the water table will not rise to the level of the emplacement drifts, the rocks making up the repository's fundamental framework will not erode, seismic effects will be minor, and the likelihood of future volcanic disruption is minimal.

The Design

In essence, the site's natural properties can contain the majority of the projected radioactive inventory (comprising some 350 different radioactive isotopes) and prevent its entering the groundwater. There is, however, a small fraction (less than 2 percent) of radionuclides that if exposed to water under the right conditions, could potentially migrate from the repository. The engineered barrier system, as part of the multiple-barrier defense-in-depth approach, addresses this concern by limiting the exposure of these radionuclides to water. The waste package, the pallet on which it sits, its protective drip shield, and the drainage system or invert that supports each of these components, as well as the transportation rails inside the emplacement drift, are all part of the engineered barrier system.

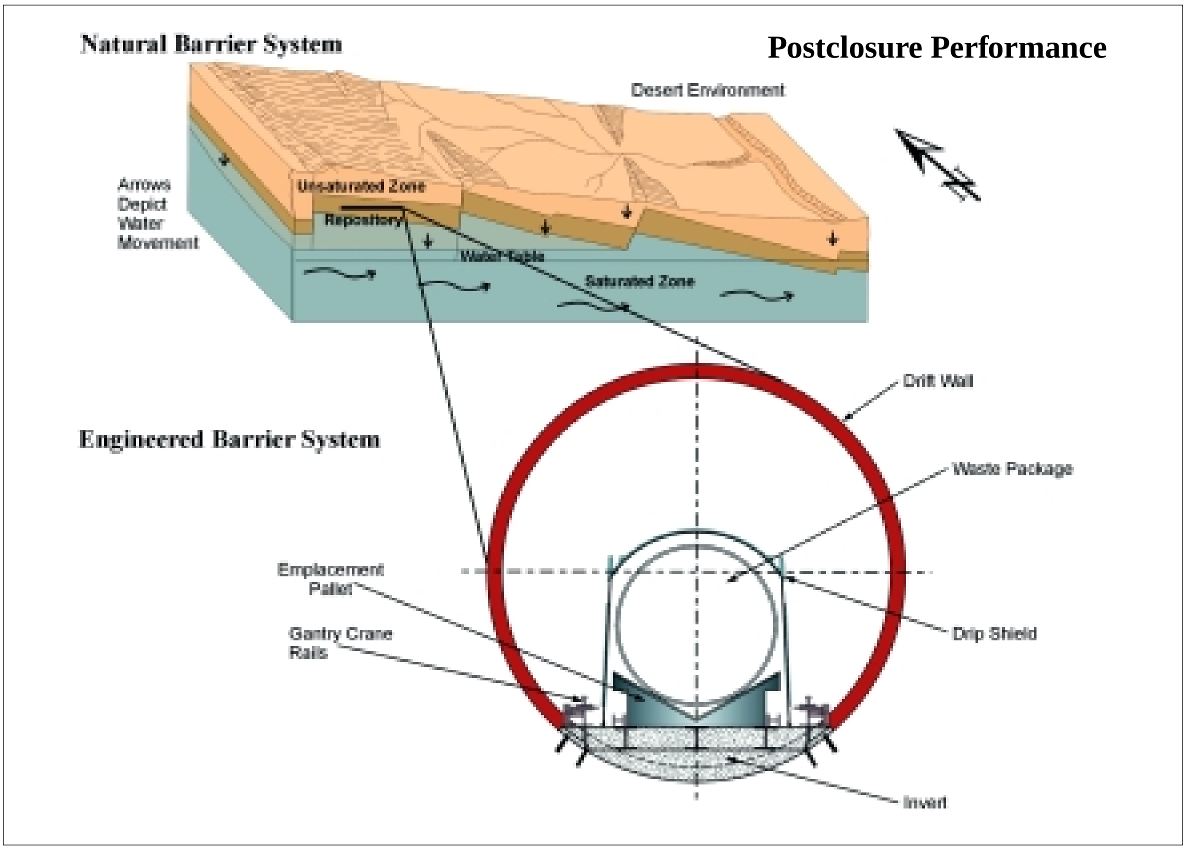

Fig. 3. A geologic repository at Yucca Mountain would rely on the area's dry climate as well as the natural and engineered barriers to contain and isolate the waste for thousands of years.

As with many long-term, complex projects, designing the repository has been a dynamic and evolutionary process. In the late 1980s, the mountain itself was considered the primary barrier to the release of radioactivity, and the waste was to be stored in individual boreholes, in either a vertical or horizontal orientation. Now, the waste package has become the focal point of waste containment, and storage will be linear in specially reinforced horizontal drifts. Furthermore, in the mid-1990s, multipurpose canisters that would meet U.S. Nuclear Regulatory Commission regulations for storage at reactor sites, transportation to the repository, and final disposal were being considered. Today, these functions have been separated—the radioactive material is slated to arrive at the repository in transportation casks and be transferred to the waste packages. The design of the waste package itself has also changed, even within the past two years. The reference design for the waste package that will be submitted as part of the Site Recommendation (SR) this year is significantly different from the design referenced in the Viability Assessment (VA) of December 1998.

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Framatome Cogema Fuels has participated in the Yucca Mountain Project since 1987 and, as part of the TRW-led management and operating contractor team, has managed the design effort for the waste package since 1991. The company is responsible for designing the waste packages (pallets and drip shields) and demonstrating the techniques and processes for their fabrication and closure, as well as for providing the data and process models for forecasting their performance under the conditions postulated for the repository over thousands of years. This latter task involves evaluating not only the possible degradation mechanisms of the waste packages themselves and their contents, but also the potential for the fissile material to become critical.

The Waste Package

While this discussion focuses mainly on the evolution of the waste package design, limiting the potential for criticality—during preclosure operations and postclosure performance—is an essential element of the repository's design. The current design calls for an open operational period of approximately 50–100 years to emplace and monitor the waste. However, provisions are included that could keep the repository open for up to 300 years with the possibility of retrieving the waste packages.

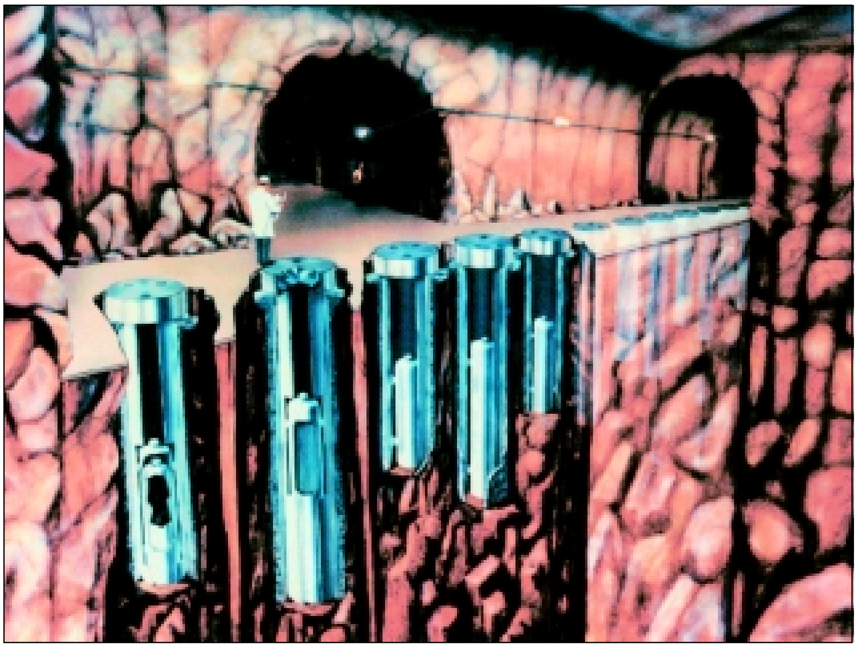

Fig. 4. The early design for the repository envisioned the waste containers being stored in vertical holes, with each hole accommodating a single canister and a closure plug providing some shielding against radiation.

The waste package touches every aspect of the repository's operation—from loading in the surface facility through transport to the subsurface facility to installation in the emplacement drift and even possible retrieval. It must therefore fulfill the following design requirements:

- Withstand handling: loading, transportation, emplacement, and retrieval.
- Prevent the release of radionuclides.
- Withstand the repository's internal environment.
- Provide criticality protection.
- Prevent adverse reactions involving the waste form.
- Provide physical and chemical stability for the waste form.
- Allow unique identification of the waste inside the package.
- Augment safety for personnel, equipment, and the environment.
- Manage the decay heat inside the repository.
- Promote and manage the heat transfer between the waste form and the mountain.
- Allow decontamination of its outer surface.

As a result, designing a waste package that not only meets all the design and performance criteria but also satisfies manufacturing and cost constraints has required an iterative approach.

As mentioned earlier, in the late 1980s, the natural features of the mountain were considered the primary barrier to the release of radioactivity. Consequently, the initial waste package was to be a thin-walled container with a design life of 300 years. This package would hold up to three fuel assemblies from a pressurized water reactor (PWR) and four from a boiling water reactor (BWR) with a maximum heat output of 3 kilowatts. More than 50 000 waste packages would have been required had this design been adopted.

The initial repository design also called for the waste packages being placed in boreholes inside the emplacement drifts. With this concept, the closure plug that sealed the borehole would provide shielding so that the drifts could be accessed after the waste packages had been installed. Two configurations were considered: vertical and horizontal. For the vertical design (see Fig. 4), boreholes would be drilled into the floor of the drift. The drifts would have multiple holes, each loaded with a small, single-purpose waste package. The second design, on the other hand, used boreholes drilled horizontally into both walls of a drift (see Fig. 5). A short borehole would be used for one or two waste packages; a long borehole would accommodate multiple packages.

A waste package with a design life of 1000 years versus 300 would significantly decrease the potential for radioactivity being released into the environment.

The borehole concept proved to have several shortcomings. First, the overall dimensions of the waste package were limited because the stability of a borehole was directly related to its size (the smaller the diameter, the more stable) and handling the packages in such confined spaces would be difficult. Second, the thermal considerations for the individual waste forms would not allow the 15-ft spacing (from center to center of the waste packages) between the boreholes that the scientists had calculated as the optimum configuration—unless major modifications were made to the overall repository. Further, governmental regulations required licensing the boreholes and the repository separately. Therefore, if a borehole were found unstable, even with a liner, it could not accept a waste package. Such obstacles reduced the appeal of the borehole approach, and the concept was abandoned in 1992.

The waste packages developed for the borehole configuration varied in design, yet they had several characteristics in common: barriers made of metals, ceramics, or composites; an ability to accommodate filler materials as buffers or barriers; and no additional shielding to reduce the radiation coming from their contents. In addition, none of the designs took advantage of the performance of backfill (a design option) in a drift.

In 1992, the design for the repository changed from relying primarily on the mountain to isolate and contain the radioactive waste to a more balanced approach between the natural and engineered barrier systems. Analyses showed that the waste package would influence the repository's overall performance and that a waste package with a design life of 1000 years versus 300 would significantly decrease the potential for radioactivity being released into the environment. A robust defense-in-depth, multibarrier design, therefore, was developed for the waste packages. In addition, the packages could hold more—21 PWR or 44 BWR spent-fuel assemblies. This increased capacity reduced the number of waste packages required to about 10 000. And, as the design for the waste package changed, so did the emplacement strategy. Installing the waste packages in geologic boreholes was replaced by emplacing them linearly in horizontal drifts (see Fig. 6). This arrangement resulted in a more stable geometry for the rock framework, easier handling of the waste package for installation and retrieval, better thermal dissipation, and a straightforward way to assess and confirm performance.

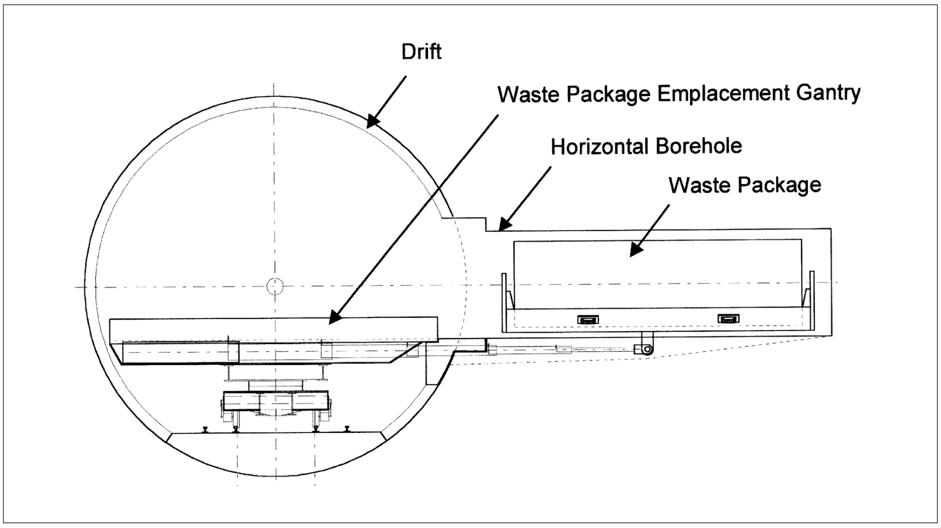

Fig. 5. Another version of the borehole concept called for placing the waste containers in holes drilled into the sides of the walls of the emplacement drifts.

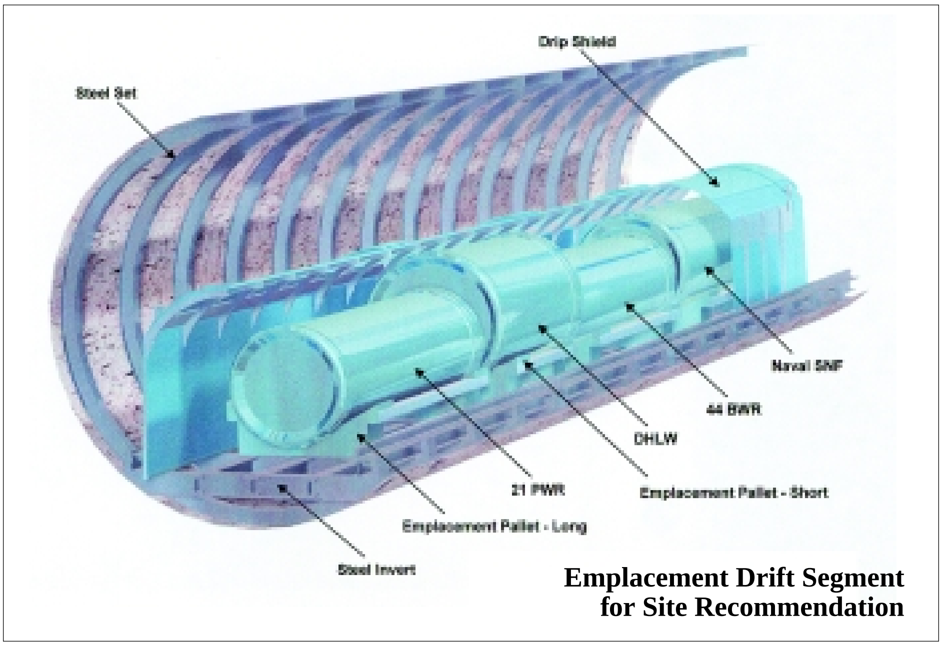

Fig. 6. The engineered barrier system, an integral part of the multiple-barrier defense-in-depth approach, limits the exposure of the waste to water. The system has four major components: the waste package, a pallet to keep it off the drift floor, an invert to support it and provide drainage for any seeping water, and a drip shield to divert any dripping water. Waste packages with commercial spent nuclear fuel, defense HLW (codisposal packages), and Navy fuel will be co-located in the emplacement drifts with their positions dictated by thermal requirements.

The Latest Version

Several versions of this larger, more robust waste package were developed during two relatively recent phases of the project: the VA and the SR, the most current design. Although the parameters and materials of these waste packages differ, the basic concept is the same—a defense-in-depth design to prevent water from contacting, and interacting with, the contents of the waste packages. Therefore, all the subsequent designs are fundamentally the same: a cylinder within a cylinder each with its own top and bottom lids, with one cylinder providing structural strength and the other, corrosion resistance. Further, the waste forms provide additional barriers against the migration of radionuclides. The cladding and non-fuel-bearing components of spent-fuel assemblies are made of corrosion-resistant materials such as Zircaloy and stainless steel, while the defense HLW will be disposed of as vitrified “glass” inside stainless steel canisters.

The physical dimensions and internal configurations for the waste packages vary based on the type of waste they contain: PWR spent fuel, BWR spent fuel, defense HLW, and Navy fuel. Their physical dimensions range from 11.5 to 20 ft in length and 4.25 to 6.9 ft in diameter; fully loaded weight ranges from about 23 to 78 tons.

The VA design included an approximately 0.75-inch-thick inner shell of Alloy 22 and an outer shell of 4-in.-thick carbon steel (see Fig. 7). The top and bottom lids were made of the same materials as their respective shells. The Alloy 22, a nickel-based alloy, was chosen for its resistance to corrosion; the carbon steel (designated A516) was selected for its structural strength. Furthermore, the two materials degrade through two different and independent mechanisms: the carbon steel through general corrosion or oxidation and the Alloy 22, through localized pitting. However, additional analyses showed that this configuration had its weaknesses and could be improved. For example, when the carbon steel degrades, it reduces both the waste package’s structural strength and its ability to resist rock-fall events. In addition, as the oxidation products of the carbon-steel degradation collect between the interface of the inner and outer shells, they produce a wedging action. By creating sufficient stresses between the Alloy 22 and the carbon steel, this wedging action might cause the thinner inner barrier to fail. Because of these findings, the VA design was officially abandoned in 1999 as other designs using different combinations of materials were being evaluated.

These evaluations yielded the SR design, also a cylinder-in-a-cylinder with the two different shell materials degrading at different rates under different conditions (see Fig. 8). This time, Alloy 22, approximately 1 in. thick, is used for the outer shell; the inner shell is made of stainless steel 316NG (nuclear grade), about 2 in. thick. The Alloy 22 provides a corrosion-resistant outer shell (primary barrier) and increases the overall design life of the waste package to more than 50 000 years, exceeding the current regulatory performance criteria requiring a minimum of 10 000 years. The stainless steel improves the waste package's performance because it is less susceptible to oxidation than carbon steel. With this combination and arrangement of materials, the corrosion-resistant outer shell protects the underlying structural material from corrosion, while the structural material supports the thinner, corrosion-resistant shell. This SR waste package has two bottom lids made of the same two materials as their respective shells; however, an additional lid has been added at the top, for a total of three lids—the inner lid is stainless steel and the outer two lids are Alloy 22. The extra lid of Alloy 22 provides an additional barrier against corrosion should the outer lid fail prematurely. The SR design also eliminates the skirt with lifting rings used in the VA design to remotely handle the waste packages. In its place, a grooved Alloy 22 collar is welded at each end of the outer shell. A detachable ring with trunnions is then placed in these grooves. The trunnions allow a stable platform for manipulating the waste packages. The rings and trunnions are removed after the waste package has been placed on its pallet.

Another feature of the engineered barrier system of the SR phase is the drip shield, which was, in fact, also a consideration for the VA design. Because the design requirements for the drip shield include corrosion resistance and structural strength, the drip shield provides an additional line of defense against water dripping or rocks falling on the waste packages. The drip shield comprises corrosion-resistant Grade 7 titanium plates for the water-diverting surfaces, Grade 24 titanium for the structural members, and Alloy 22 for the feet. They are uniformly sized so

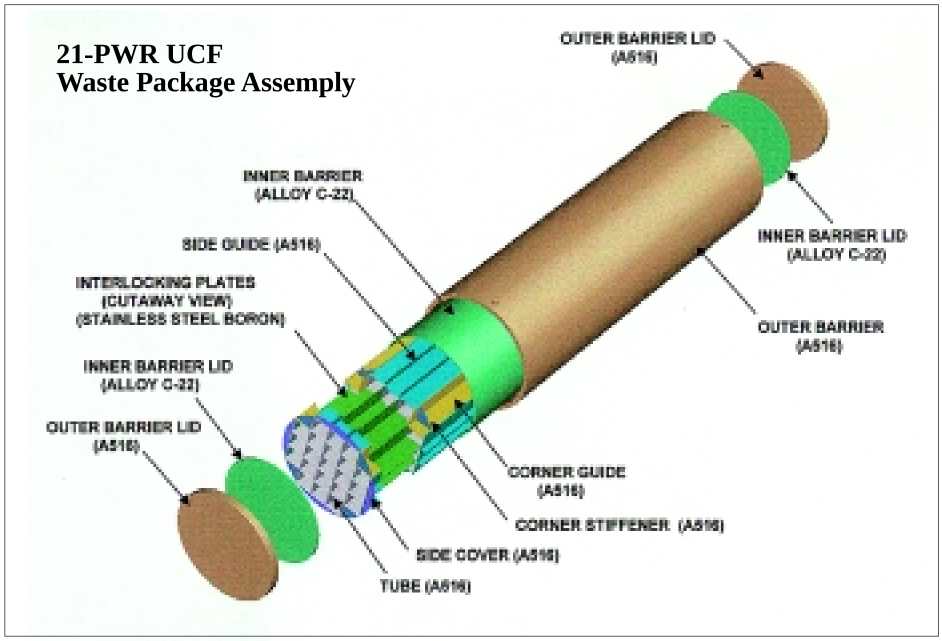

Fig. 7. The VA design for the waste package included a thick outer layer of carbon steel and a thinner inner layer of nickel-based alloy. The carbon steel provided structural strength while the Alloy 22 offered resistance to corrosion should the outer layer be penetrated.

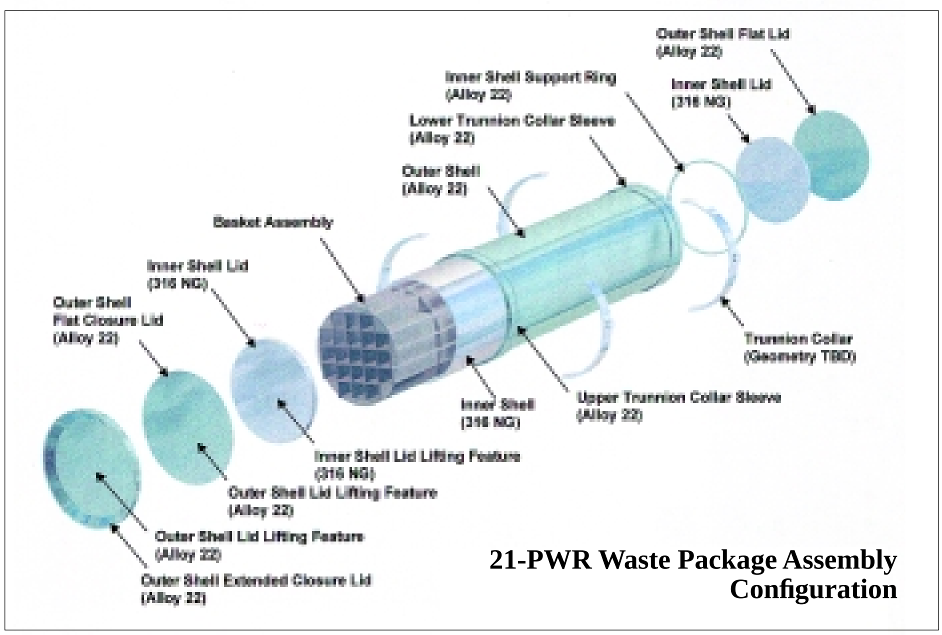

Fig. 8. Also a cylinder-in-a-cylinder, the SR design for the waste package uses an outer shell of Alloy 22 and an inner shell of nuclear-grade stainless steel. This configuration increases the expected life of the waste package to more than 50 000 years.

one design accommodates all waste-package types.

Changes Ahead

While the SR design for the waste package is the most current, undoubtedly it will continue to evolve and improve as more scientific studies are conducted, more data are collected, and regulations change or are added. The basic design will probably remain the same, though changes in material thickness or variations in geometry are likely to occur.

Other changes to the overall repository design and operation are also currently being evaluated. For example, the DOE is considering a thermal option as a part of the repository's flexibility. This option would keep the temperature of the emplacement-drift walls below the boiling temperature of water (96°C at the elevation of Yucca Mountain). Backfilling the emplacement drifts just before the repository closes is another feature under consideration. While the timeline for the decision on these choices is uncertain, one thing *is* certain—every option for, every improvement to, the engineered barrier system is discussed, evaluated, and either discarded or implemented with a view to minimizing the environmental impact of the repository and ensuring the success of this first-of-a-kind project. ■

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