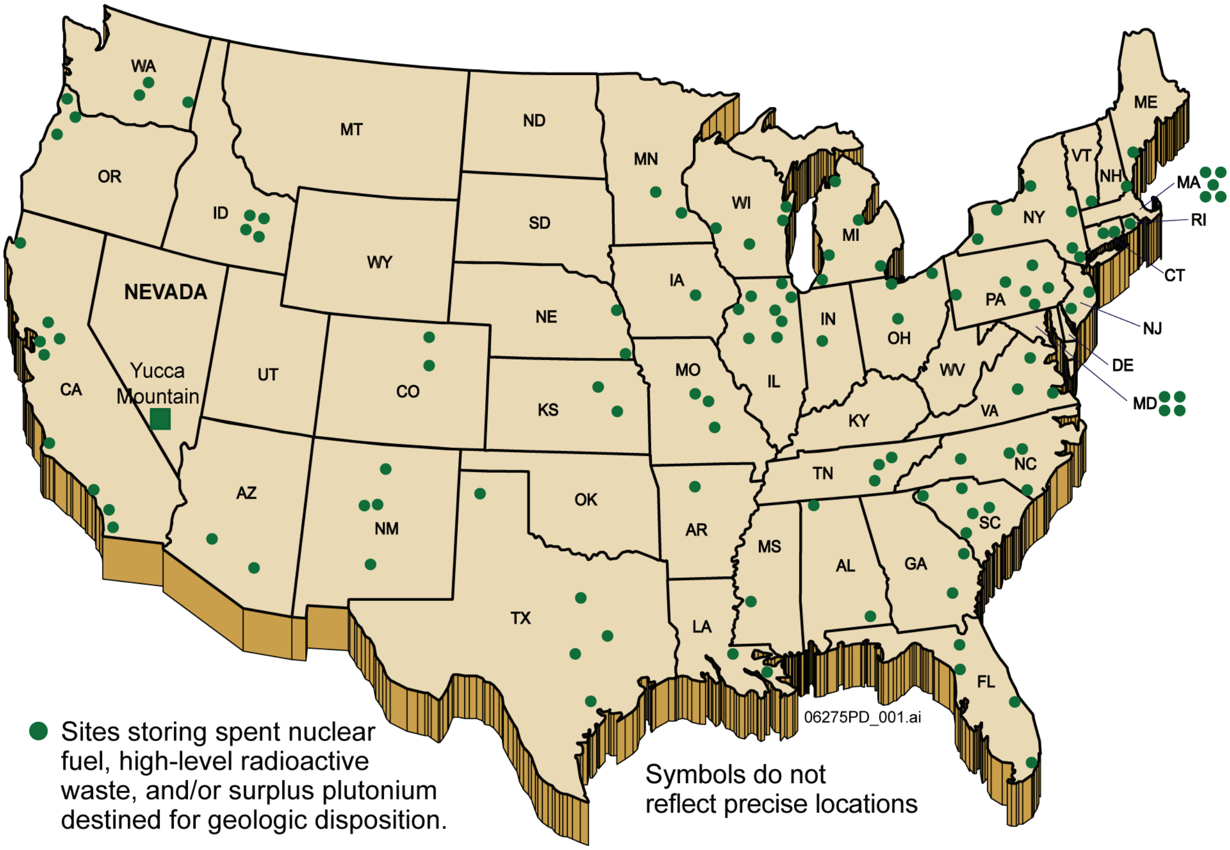



# The Safety of a Repository at Yucca Mountain



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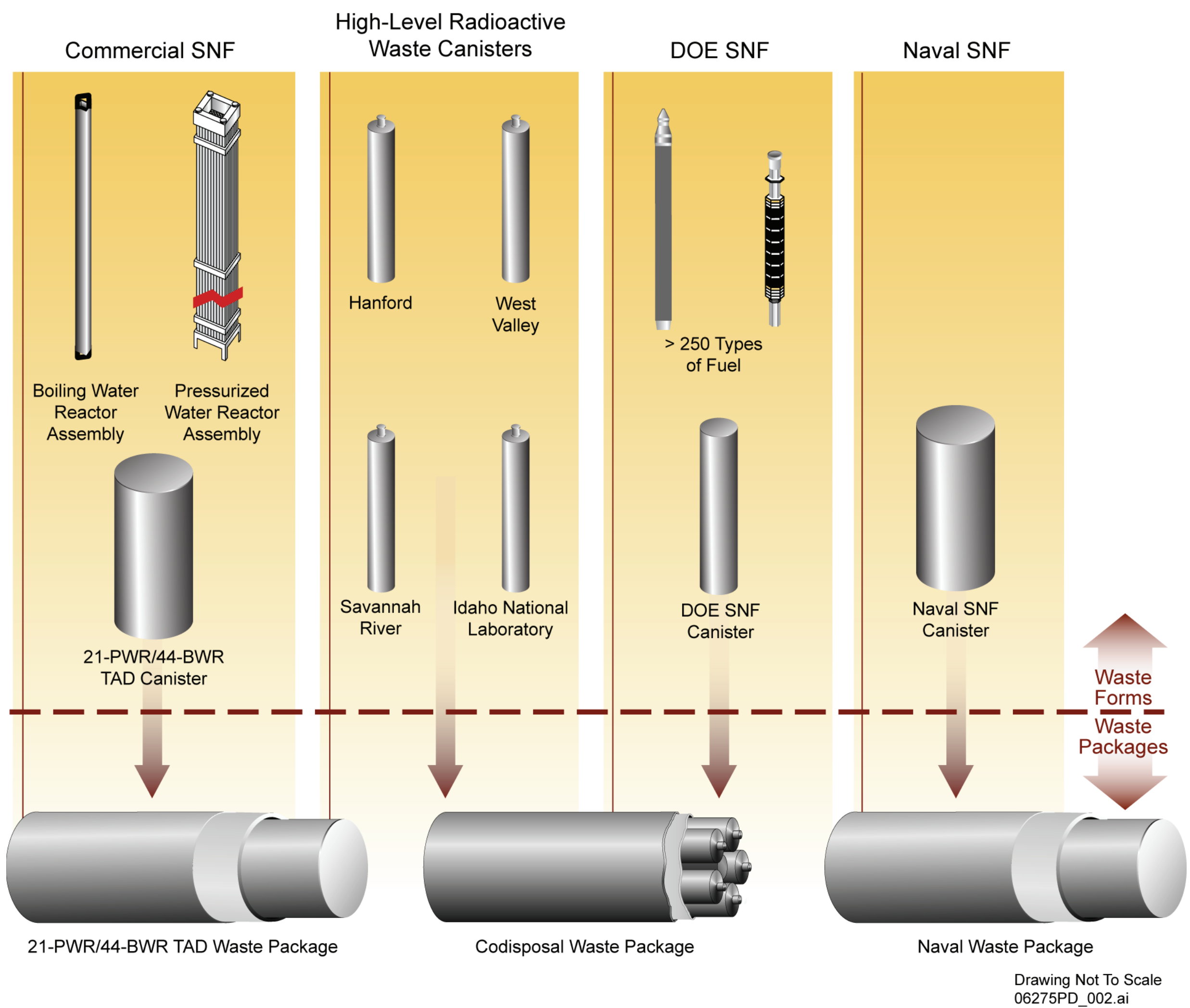
Sites storing spent nuclear fuel, high-level radioactive waste, and/or surplus plutonium destined for geologic disposition.
Symbols do not reflect precise locations

Commercial SNF
High-Level Radioactive Waste Canisters
DOE SNF
Naval SNF
Boiling Water Reactor Assembly
Pressurized Water Reactor Assembly
Hanford
West Valley
> 250 Types of Fuel
21-PWR/44-BWR TAD Canister
Savannah River
Idaho National Laboratory
DOE SNF Canister
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Waste Forms
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U.S. Department of Energy

Office of Civilian Radioactive Waste Management


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# The Safety of a Repository at Yucca Mountain

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# The Safety of a Repository at Yucca Mountain

## 1. Introduction

The U.S. Department of Energy (DOE) has now submitted a license application to the U.S. Nuclear Regulatory Commission (NRC) to construct a geologic repository at Yucca Mountain, Nevada, for the disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW). The submittal of the license application is a major milestone in the history of site investigations, scientific analysis, and repository facilities design and is a major step toward safe, permanent disposal of nuclear waste.

This work was begun more than 25 years ago, when Congress adopted the Nuclear Waste Policy Act (NWPA), consistent with the overwhelming consensus in the international scientific community that the best option for a disposal facility for nuclear waste is a deep underground repository. More than 20 years ago, Congress directed the Secretary of Energy to investigate and recommend to the President whether such a repository could be located safely at Yucca Mountain. Following tens of millions of hours of research to answer this question, the Secretary recommended to the President that Yucca Mountain be developed as the site for an underground repository for spent fuel and other radioactive wastes. The Secretary also concluded that there are compelling national interests in favor of proceeding with the project. These national interests included national security, nonproliferation objectives, energy security, homeland security, and efforts to protect the environment. The President approved the recommendation, and in July 2002 the President signed the joint Congressional resolution known as the Yucca Mountain Development Act, designating the Yucca Mountain site for development as a repository for the disposal of SNF and HLW. This action authorized the DOE to proceed in the development of a license application and to seek approval from the NRC to construct a repository. At a later date, a separate licensing decision by the NRC will be required before the repository can commence operations.

The Yucca Mountain repository Construction Authorization license application, which the DOE submitted to the NRC in June of 2008, describes the results of scientific and engineering studies of the Yucca Mountain site, the waste forms to be disposed, the repository and waste package designs, the results of safety assessments of the operations to be carried out at the repository, and evaluations of the long-term performance of the repository, along with general and administrative information. The license application provides the information specified by the NRC in its regulations and other guidance documents. The license application contains results of long-term safety evaluations based on studies of the geologic, hydrologic, and geochemical environment and evaluations of how conditions might evolve over time. These evaluations consider a range of processes that could affect the repository. Because projections of performance for 10,000 years and longer are inherently uncertain, the uncertainties associated with analyses and models of long-term performance are also described in the license application.

This document presents a summary of why the DOE has concluded that it can safely construct and operate a repository for SNF and HLW at Yucca Mountain in Nye County, Nevada and demonstrates that the repository system will safely limit releases well into the future. The conclusion that the repository will be safe if constructed and operated as described in the license application is based on DOE assessments of the ability of the repository to meet EPA standards and NRC regulations governing a repository at Yucca Mountain. This document presents an overview of the evidence, analyses, and conclusions that quantify and substantiate the DOE position that the repository will be safe during operations and after closure, beyond the time when active control of the facility is needed or can be relied on, and it presents a summary of the safety findings. The document discusses the safety of the repository in two time frames: (1) during the operation of the repository, while wastes are shipped to Yucca Mountain, packaged and placed underground, and monitored; and (2) after the repository is permanently closed. Each of these sections is organized to describe the safety principles governing the design and safety assessments, to present a description of the features or components of the repository that are important to demonstrating safety, and to present a summary of pertinent results accompanied by a discussion of why the DOE has confidence in the results.

**mrem.** The millirem, or mrem, is a measure of the amount of radiation a person receives and how it affects the body. One mrem is less than 0.5% of the amount of radiation received annually from naturally occurring radiation. 1,000 mrem is equal to 1 rem.

The DOE has addressed the potential risks associated with the handling and disposal of radioactive wastes in preparing the license application and its environmental impact statements. The handling and disposal of radioactive wastes are governed by standards and regulations issued and administrated by the EPA and the NRC, respectively. These standards and regulations specify maximum permissible levels of radiation doses, measured in millirem or rem, to workers and the public. The DOE must comply with these regulations and, in order to do so, must examine how the repository is expected to perform under expected or normal conditions as well as in response to the impact of potential hazards and very low probability events that could disrupt the repository system.

The detailed assessments establishing the safety of the repository are presented in the license application. As shown in the application and summarized in this document, the potential doses to workers and the public from the operation of the repository are below the limits imposed by the regulations. The same is true for protection of the public after the repository is permanently closed. In fact, the estimated doses to the public in the distant future are a small fraction of the limits imposed by the proposed regulations. The doses are calculated for a hypothetical individual designed by regulation to be situated in a manner to maximize the calculated dose. The expected doses to real people, especially those with an urban lifestyle, would be smaller. These projected estimates represent a very small fraction of the background radiation that all Americans receive just from living in the United States.

# 2. Contributions to Safety by the Site, the Materials to Be Disposed, and the Repository Design

## 2.1 SITE DESCRIPTION AND SELECTION

Internationally, there is a consensus that geologic disposal is the best means for final disposal of SNF and HLW, that geologic disposal can be safe, and that the regulations and analytical approaches used to demonstrate such safety are reasonable. The science supporting the understanding of Yucca Mountain has been developed over more than 30 years by world-recognized experts and has been internationally reviewed. Scientists from the country's National Laboratories, including Sandia, Los Alamos, Lawrence Livermore, Lawrence Berkeley, and Argonne, have been involved since the program's beginning. Internationally recognized experts from the U.S. Geological Survey were responsible for the suggestion to look to the unsaturated zone (see below) for repository development to take advantage of the conditions of limited water. The engineering designs were developed to complement the site's unsaturated characteristics and, especially for the operational period, to build upon decades of precedent experience in the safe handling of SNF and other radioactive materials.

Yucca Mountain was one of nine sites initially studied for the first repository under the NWPA. Its identification as a potential site followed early work by the U.S. Geological Survey showing that disposal in the unsaturated zone would offer advantages in deep geologic disposal of SNF and HLW. The conclusion was based on the premise that, because water was the medium that would eventually transport radionuclides away from the repository, a repository site in an environment with limited water would be a benefit to repository performance that was provided by the natural system.

**unsaturated zone.** The unsaturated zone is the zone between the land surface and the regional water table. The rocks in this zone are not completely dry, but the pore spaces are only partially filled with water. The water is held in the pores, which prevents it from moving freely, giving the unsaturated zone its unique character.

The Yucca Mountain site, shown in Figure 1, is located on federal land adjacent to the Nevada Test Site in Nye County, Nevada, about 90 miles northwest of Las Vegas. The mountain consists of a series of ridges extending 25 miles from Timber Mountain in the north to the Amargosa Desert in the south. The water table at Yucca Mountain is approximately 1,600 to 2,600 ft below the surface of the mountain at the repository location. The underground facility will be located in the unsaturated zone, about 660 to 1,600 ft below the surface and, on average, about 1,000 ft above the water table. The deep water table and thick unsaturated zone at Yucca Mountain are the result of the low infiltration rate of surface water due to low annual rainfall and high rates of evaporation and transpiration (the process by which water passes from soil into plants and then into the air).

The repository will be located in volcanic rock called tuff that was deposited by a series of eruptions between approximately 11 and 14 million years ago. The characteristics of the volcanic rock have been studied in underground excavations and boreholes and by extensive geologic mapping of the surface. Mapping and other studies show that faults are present in the vicinity of Yucca Mountain. The location, timing, and amount of movement on these faults have been characterized as part of the DOE seismic hazard analysis. The location of the underground facility was identified using several factors, including the thickness of overlying rock and soil, the characteristics of the rock that would host the repository, the location of faults, and the depth to groundwater. The facility will be sited

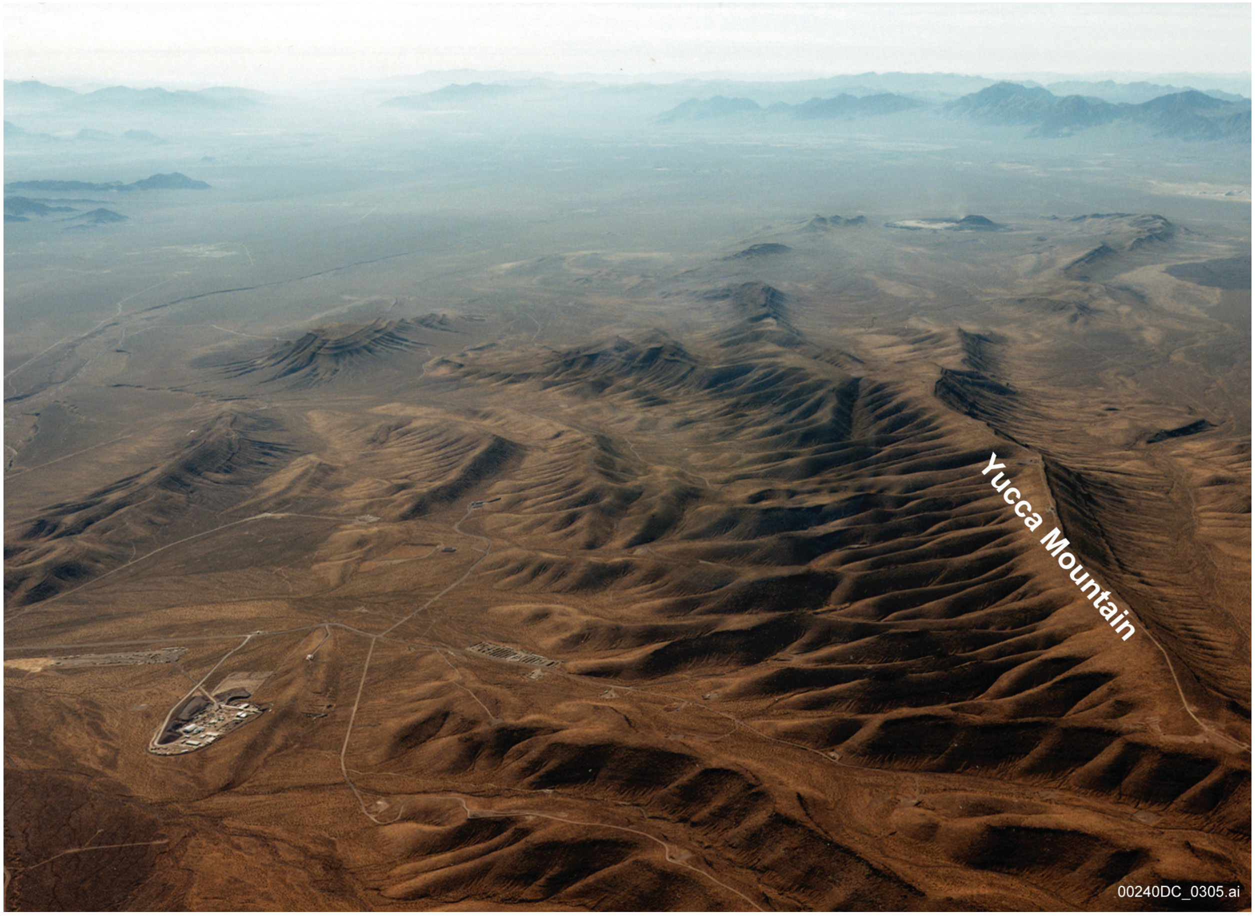



Figure 1. Photograph of the Yucca Mountain Site

deep enough underground to prevent waste from being exposed to the environment and to prevent accidental human intrusion. The host rock for a geologic repository must be stable enough to sustain excavated openings during repository operations. The rock must also be able to absorb heat generated by the SNF and HLW. The Topopah Spring Tuff rock unit in which the underground facility will be constructed exhibits these characteristics.

The combination of the desert environment and the deep water table with the thick unsaturated zone between the surface and the water table define the hydrologic nature of the repository system at Yucca Mountain. The desert environment with its low rainfall and limited infiltration of water into the subsurface is a favorable long-term characteristic of the Yucca Mountain setting. Far in the future, the return of glacial climate conditions to North America would still leave Yucca Mountain in a desert environment. The location of the site significantly contributes to the inherent safety of repository operations. The site boundary is approximately 5 miles away from the waste handling facilities, and there are no permanent residents within approximately 14 miles of the repository. This remote location reduces the effects of potential radioactive releases from normal operations and the abnormal, highly unlikely events considered in the safety analysis. There are design features of the repository and waste handling operations facilities that prevent unlikely events or reduce their potential impact. These safety-enhancing design features are comparable to proven features currently required of nuclear power plants.

Following the process required by the NWPA, Yucca Mountain was one of the five sites originally nominated by the Secretary as suitable for site characterization for selection of the first repository site. Yucca Mountain was one of the three sites recommended by the Secretary to the President as candidate sites for site characterization. Those recommendations were approved by the President. DOE documents that compared the sites at that time showed Yucca Mountain to be one of the best performing sites for long-term safety out of the nine sites initially considered. As noted, the site recommendation and subsequent 2002 decision by Congress to designate Yucca Mountain as the site for development of the repository allowed the DOE to prepare the license application. A license application is the formal document an applicant submits to the NRC to describe proposed activities and document the safety analyses for those activities. The NRC evaluates an applicant's proposed activities and safety analyses through an extensive review of the license application. The NRC must approve the license application before construction of the repository is allowed to take place.

## 2.2 THE NATURE OF THE MATERIALS TO BE DISPOSED AND THE WASTE PACKAGES TO BE USED

The numerous locations where SNF and HLW is currently stored across the United States are shown in Figure 2. The waste forms transported to and received at Yucca Mountain will be solid and robust materials. No liquid waste forms will be accepted for disposal.

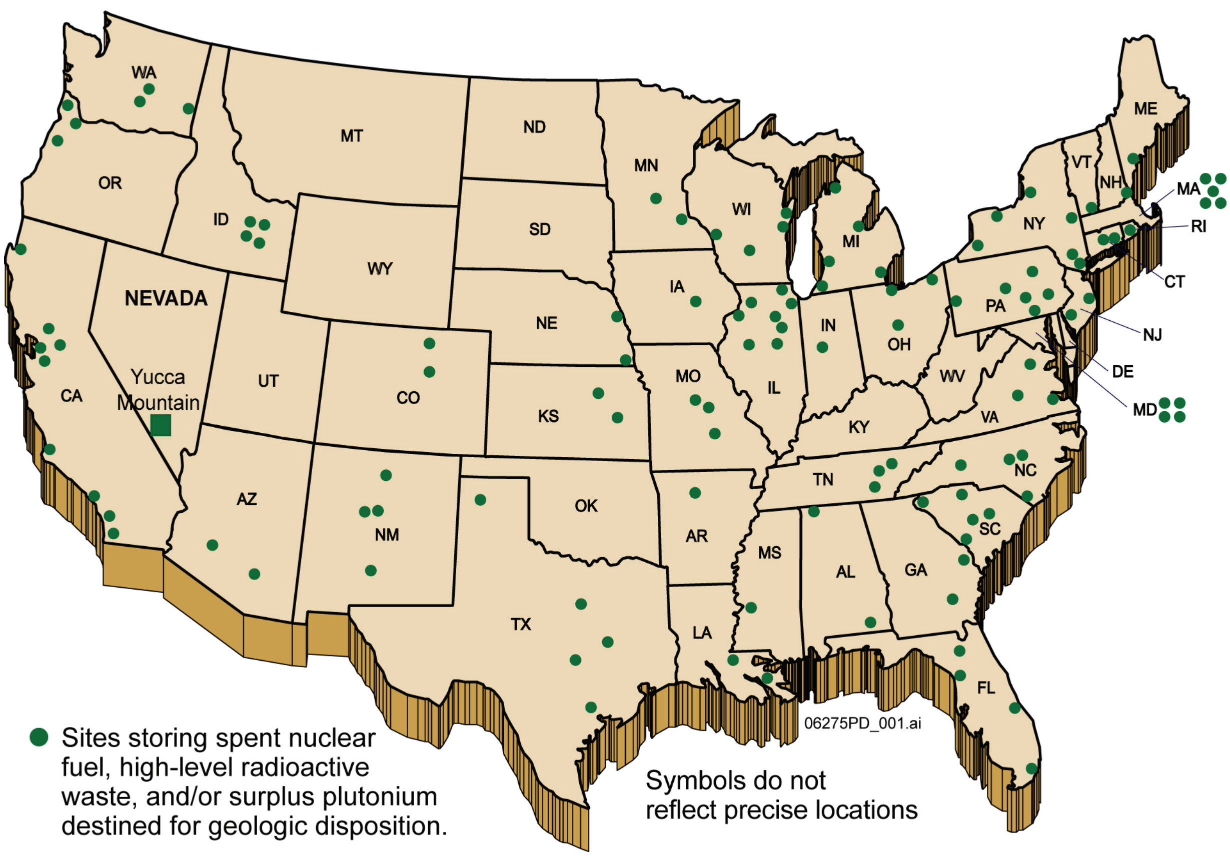



Figure 2. Current Locations of Nuclear Waste Storage Across the United States

Figure 3 shows the types of waste that will be emplaced at the repository. By statute, the DOE is responsible for the safe, permanent disposal of SNF from commercial nuclear power plants. The SNF consists of bundles of rods containing a ceramic uranium oxide fuel and is currently stored by each utility. This ceramic is very resistant to being dissolved. The DOE will also dispose of DOE-owned HLW from the past production of nuclear weapons and smaller quantities of SNF from weapons production reactors, research reactors, and naval reactors. The majority of the DOE SNF is currently stored at DOE sites in Idaho, South Carolina, and Washington state. In addition, the liquid waste from past nuclear weapons production programs is stored in underground tanks at the same DOE sites. Before disposal at Yucca Mountain, this liquid waste will be mixed with silica sand and other constituents, melted together to form a glass, and poured into stainless steel canisters. Once the glass solidifies (vitrifies), the canister will be sealed. When the repository is ready to receive the canisters, they will be loaded into transportation casks and shipped to the repository. Vitrified waste does not dissolve easily and will stay intact for many thousands of years. There is also a small amount of vitrified HLW from a past commercial SNF reprocessing activity that the DOE will receive and dispose of at the repository.

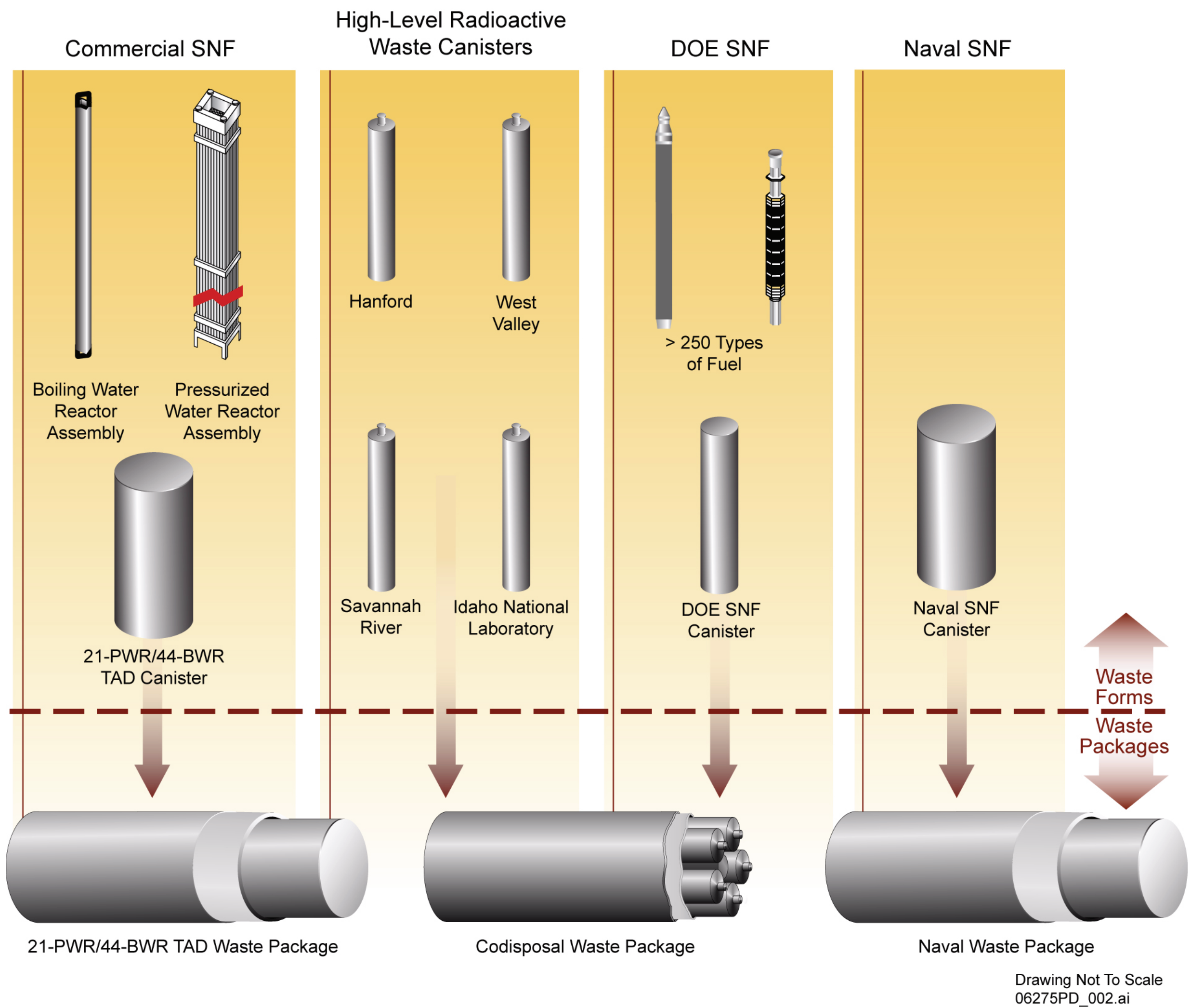



Figure 3. Types of Waste to be Emplaced at the Yucca Mountain Repository and the Waste Packages They Will Be Disposed In

Some of the material that will be disposed in the repository will come from surplus plutonium resulting from the decommissioning of nuclear weapons. Current plans call for the surplus plutonium to be combined with uranium to form fuel that will be used in commercial reactors. The resulting spent fuel will be disposed as commercial SNF. It is likely that more than the Yucca Mountain repository's regulated capacity of 70,000 metric tons of heavy metal (metric tons of heavy metal is the measure for expressing the quantity of SNF specified by Congress in the NWPA) of SNF and HLW will exist in various storage facilities by 2010 (Figure 2).

The waste packages into which the SNF and HLW will be placed are also robust and extremely resistant to corrosion. The waste packages are made of two concentric cylinders. The outermost cylinder of the waste package will be made of a highly corrosion-resistant nickel-based alloy called Alloy 22, which is known for its great resistance to corrosion. The inner cylinder is made of stainless steel and is also very corrosion resistant. Analyses presented in the license application show that, absent unexpected seismic or igneous events, these robust waste packages will last for hundreds of thousands of years.

Most of the SNF will arrive at the repository in a standardized canister known as the transportation, aging, and disposal (TAD) canister. This canister is also made of stainless steel and will be placed inside the other two cylinders, as shown in Figure 4.

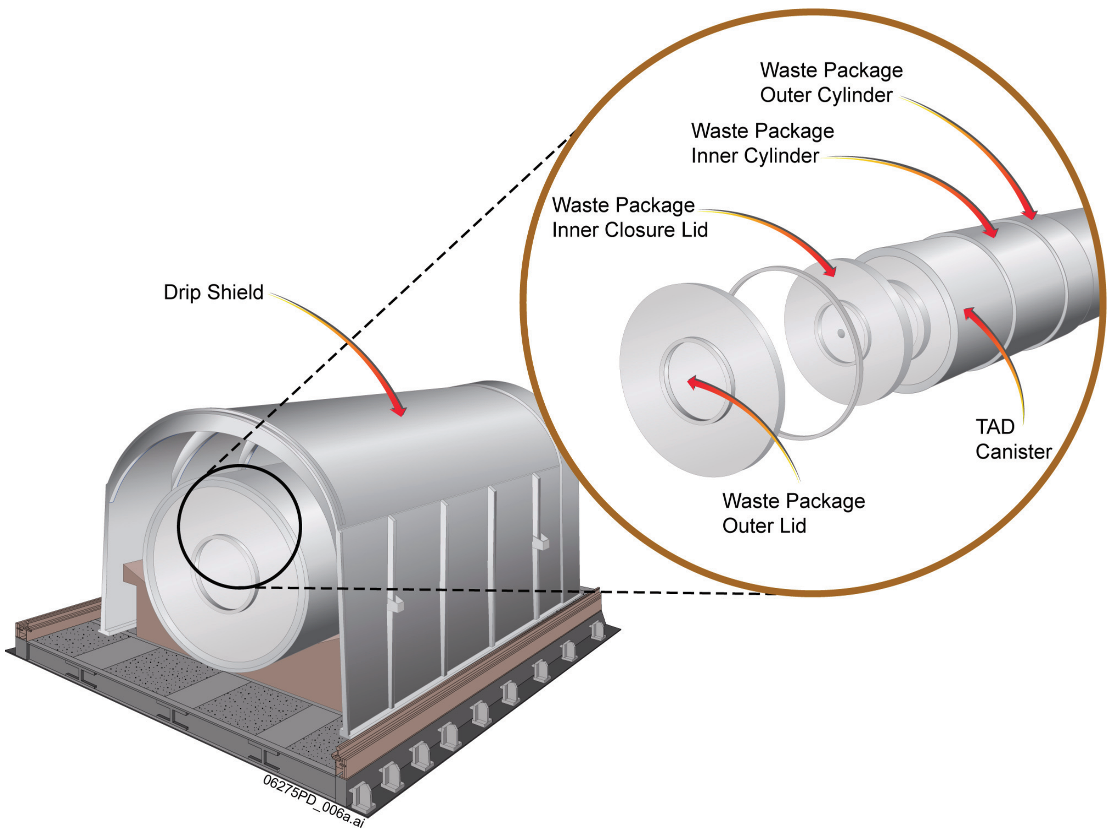



Figure 4. Schematic of TAD Canister Shown Placed inside Waste Package

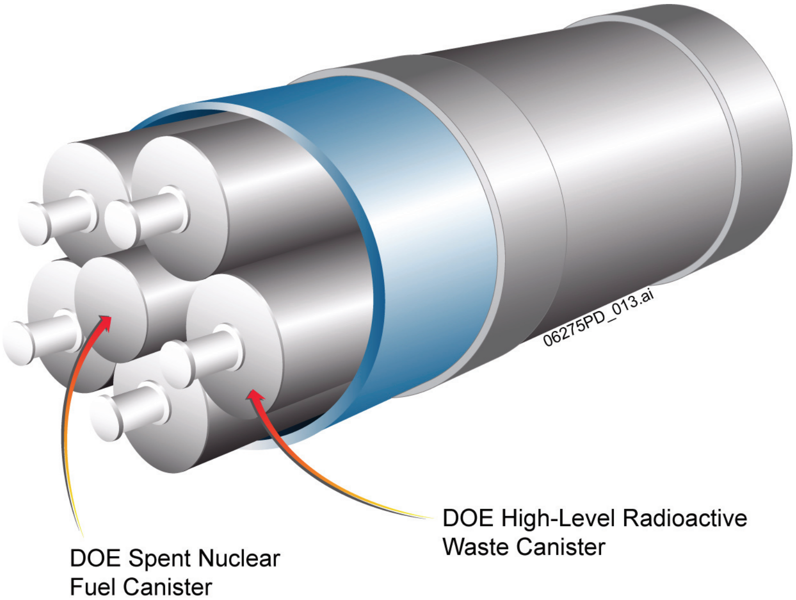



Figure 5. Schematic of DOE HLW Canister and DOE SNF Canister Placed in Waste Package

SNF that does not arrive in TAD canisters will be placed in a TAD canister at the repository. Naval SNF will arrive in a canister that will be placed in the waste package. The stainless steel canisters of vitrified HLW will also be placed inside the two cylinders of the waste package as shown in Figure 5. The figure also illustrates a center canister that will contain DOE SNF to be placed in the canister before shipment to Yucca Mountain.

Before closure of the repository, another metal layer will be placed over the waste packages to provide additional protection against the possibility of water contacting the wastes. The drip shield, shown in Figure 4, will be made of titanium, another extremely corrosion-resistant metal. All together, there will be four separate layers of highly corrosion-resistant metal protecting the wastes, which are mostly ceramic with a metal cladding and glass, both of which are themselves highly resistant to dissolution.

## 2.3 REPOSITORY DESIGN

The repository design consists of surface and subsurface facilities that perform the functions necessary to receive and handle SNF and HLW, to place these materials into waste packages, to place these packages underground, and to monitor them until closure. Several of these functions are illustrated in Figure 6.

**Surface Facilities**—The principal surface buildings of the repository are the facilities that receive, stage, age, package, and support emplacement of waste (Figure 7). Wastes will be prepared for disposal in one of three types of facilities: the Initial Handling Facility, the Canister Receipt and Closure Facility (three of which will be constructed), or the Wet Handling Facility. The repository surface facilities are based on the concept of handling mostly (about 90%) canistered commercial SNF, with a small amount (about 10%) of the expected commercial SNF arriving either uncanistered in transportation casks or in dual-purpose containers that will need to be reopened and the wastes placed in TAD canisters. The vast majority of waste will arrive in a TAD canister loaded at the electric power company sites prior to shipment to Yucca Mountain. This will minimize the amount of handling needed for uncanistered commercial SNF at the repository. The Initial Handling Facility is capable of handling and transferring canistered waste to waste packages, including HLW and naval SNF. There are three Canister Receipt and Closure Facilities planned for the repository. These facilities are capable of receiving and handling commercial SNF in TAD canisters, placing them into waste packages, and closing the waste packages. The Canister Receipt and Closure Facilities also can handle HLW canisters and DOE SNF canisters.

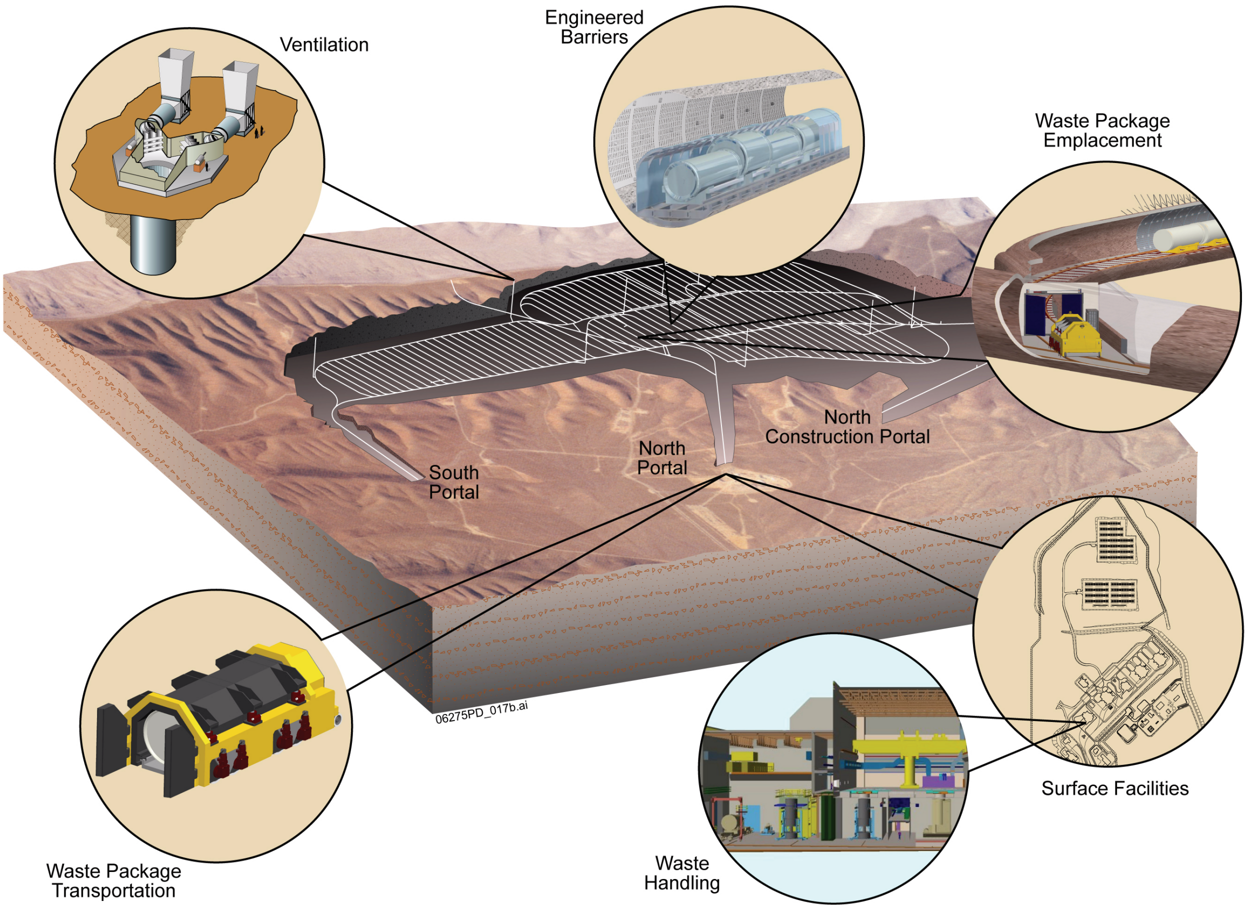



Figure 6. Repository Design Components and Functions

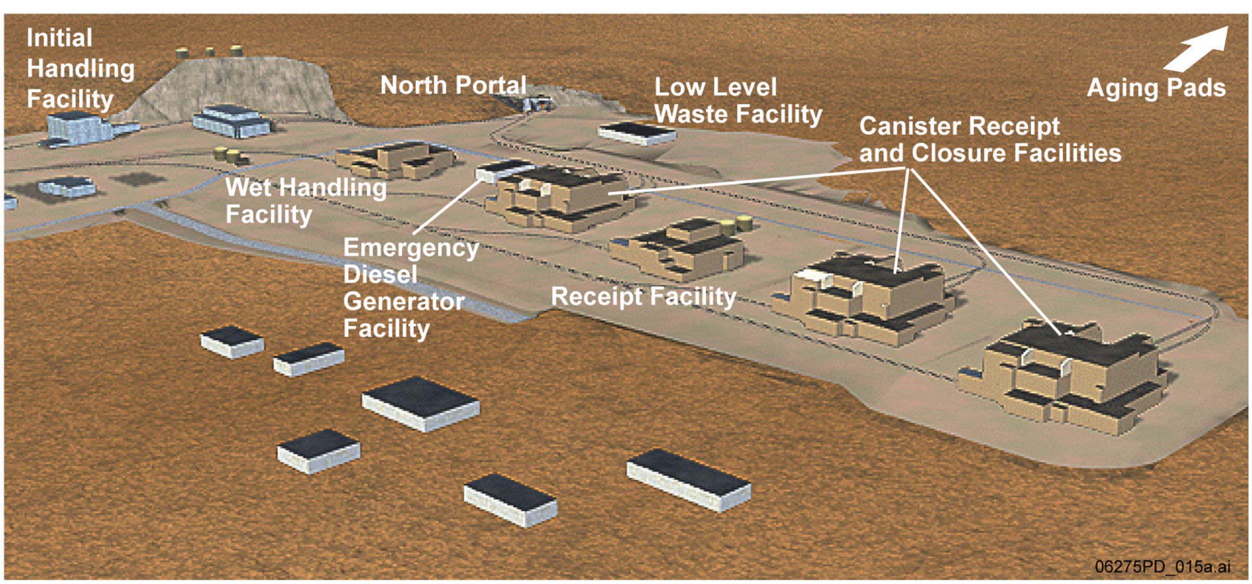



Figure 7. Representation of Principal Surface Buildings of the Repository

The Wet Handling Facility is designed to receive uncanistered commercial SNF. Commercial SNF is transferred under water in a pool into TAD canisters. The Wet Handling Facility includes provisions for handling SNF assemblies in a pool to provide shielding for workers to reduce the normal operating dose associated with handling uncanistered fuel assemblies. Commercial reactor sites already have such facilities; therefore, the repository is using well-developed and well-understood technology that has a record of safe operation.

The Aging Facility consist of the aging pads that provide safe cooling of commercial SNF until the thermal heat load of the SNF has decayed to a level low enough to be safely placed in a waste package. The design of the aging pads, aging overpacks, and TAD canisters is similar to existing dry cask storage systems used at nuclear utilities.

**Subsurface Facilities**—Waste packages will be placed underground in emplacement drifts, supported on emplacement pallets, and aligned end-to-end on the engineered drift invert. The emplacement drifts will be excavated by a tunnel boring machine that makes a circular opening. The invert is what is placed on the bottom of the drift to provide a flat surface. The packages will be spaced about 4 in. apart. The design includes area for up to 108 horizontal emplacement drifts excavated to a nominal 18-ft diameter at a center-to-center drift spacing of about 265 ft. The total subsurface area required to accommodate 70,000 metric tons of heavy metal is about 1,250 acres. The underground facility will be constructed over a period of about 30 years.

Waste packages will be moved, one at a time, from the surface to the emplacement drifts by way of a connecting rail system. The loaded transport and emplacement vehicle will move down the North Ramp and through the repository's main access drift to an emplacement drift and the designated position inside the drift (Figure 8). Before the repository is permanently closed, overlapping and interlocking drip shields will be placed over the waste packages to divert any water that might drip from the top of the emplacement drifts.

Emplacement operations will take place in finished emplacement drifts at the same time as future emplacement drifts are being constructed. During construction, separate ventilation systems operating on the development side and the waste emplacement side will allow separate control of airflow to accommodate different needs and to protect workers. During emplacement, and for the entire time before permanent closure, ventilation will maintain temperatures within the ranges selected for operation and preclosure monitoring. As part of a program to evaluate the repository performance, there will be instrumentation to allow monitoring of emplacement drift interactions with the emplaced wastes. The entire system will be monitored until permanent closure.

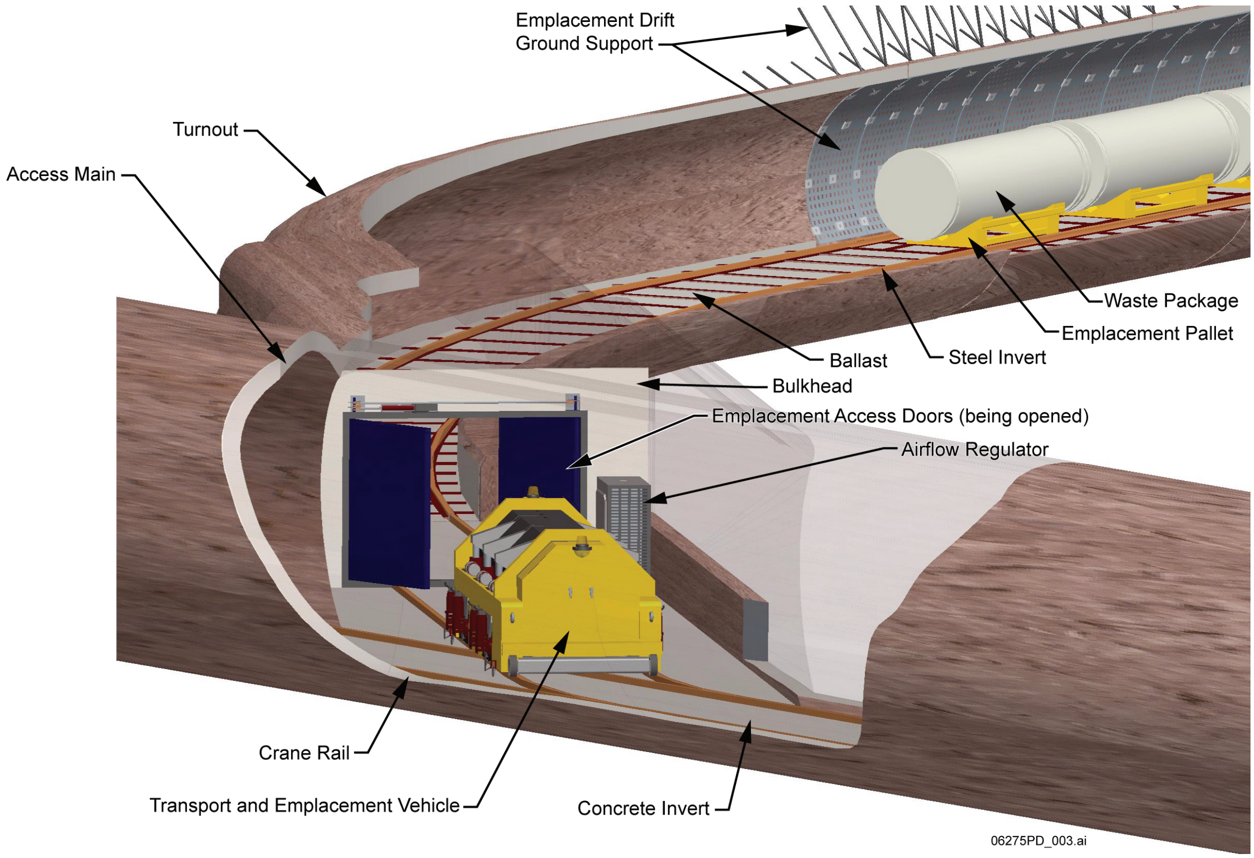



Figure 8. Depiction of the Transportation and Emplacement Vehicle Moving into to an Emplacement Drift to Emplace a Waste Package

# 3. Safety during the Operations Period

The safety principles implemented in the design of the surface facilities are to prevent events that can be foreseen and to make responses to any events that occur as automatic as possible. Accordingly, the surface facilities are designed (1) to give priority to preventing events (i.e., reducing the likelihood of occurrence) rather than mitigating consequences (i.e., reducing the impact if they should occur); (2) where it is appropriate, to use engineering features in preference to administrative controls to prevent events; (3) to rely on passive features rather than active features or controls; and (4) to allow the automatic startup of safety equipment rather than requiring human intervention to start the equipment. A design that employs this safety philosophy results in a facility with less overall risk. Operational complexity is also reduced because safety features are simple and robust, automatically initiating if there is a need.

**Features of the Repository Facilities that are Important to Safe Operations**—The repository facilities are designed to protect workers and the public. Safety analyses are used to develop a design that prevents, to the extent practical, event sequences that could lead to the release of radioactive material or result in radiological exposure of workers or the public. This strategy requires using prevention features in the repository design wherever reasonable. Information is developed to identify (1) the essential safety functions needed to ensure worker and public safety, (2) the components relied on to ensure these essential safety functions are performed with a high degree of reliability and with margin, and (3) the administrative and procedural safety controls that, in conjunction with the repository design, ensure operations are conducted safely.

The design incorporates the means to limit concentration of radioactive material in air. Design features are incorporated to minimize and control the flow of airborne contaminants. Areas of potential contamination are identified and evaluated. Heating, ventilation, and air conditioning systems capable of limiting the spread of airborne radioactive contamination are provided in the surface handling facilities. These systems control the flow of air from areas with a low potential for contamination to areas with a higher potential for contamination. These systems ensure that radiological material released due to a potential breach of a waste container will pass through high-efficiency particulate air (HEPA) filters prior to exhaust to the atmosphere, thereby mitigating the consequences of this event sequence and protecting workers and the public from releases of radioactive material. The sampled air is continuously monitored for radioactivity by monitors located in potential release points in the surface facilities.

The heating, ventilation, and air conditioning systems are designed to minimize the spread of radioactive contamination by filtration zones and to ensure air flows from areas of low potential contamination toward areas of higher potential contamination. For example, the subsurface ventilation system is designed to have two separate systems for the ventilation of the emplacement drifts and the development area. The air flow and pressure differential between the construction side and emplacement side of the subsurface repository is maintained to ensure that airflow leakage travels from the construction side (supply positive pressure system) to the emplacement side (exhausting negative pressure system) of the subsurface repository. Thus, any leakage that could occur in the emplacement portion of the subsurface would not leak to the construction side.

The design protects workers from exposure to radiation by limiting the time required to perform work in the vicinity of radioactive materials. Design features and controls are implemented to reduce the time required to work in radiological areas during normal operations, consistent with design principles that ensure radiation dose levels are as low as reasonably achievable. Access to high radiation areas or airborne radioactivity areas is controlled, which limits the potential for workers to be exposed to radiation. This includes access control to and within restricted areas. Controlling personnel access to normally unoccupied high radiation areas, very high radiation areas, or airborne radioactivity areas is part of normal operations. Suitable shielding is provided to protect workers from exposure. Shielding materials absorb radiation and protect workers in the areas where wastes are handled and in transportation underground. The pool of the Wet Handling Facility provides shielding, as do thick concrete walls and appropriate liner material.

A radiation alarm system to warn of significant increases in radiation levels, concentrations of radioactive material in air, and increased radioactivity in effluents will be used. Alarm annunciation will occur if a threshold radiation level has been reached, allowing workers to take appropriate action to protect themselves. Radiation detectors are interlocked with shield doors to ensure that the shield doors are not inadvertently opened if high radiation conditions are present. The facilities incorporate appropriate explosion and fire detection systems and appropriate suppression systems. Related controls include limiting the presence of combustibles and flammable material in areas in which SNF or HLW are present. The design includes the means to control radioactive waste and radioactive effluents and to permit prompt termination of operations and evacuation of personnel during an emergency. These functions protect workers and the public from exposure to radiation.

The design process identifies those structures, systems, and components that are important to safe operation of the repository. The process also provides the assurance that the intended safety functions will be performed. Reliable and timely emergency power will be provided if there is a loss of primary electric power so that instruments, utility service systems, and functions important to safety will continue to operate. Redundant diesel generators and filtration systems are provided as needed to maintain, with adequate capacity, the continued operation of important safety functions.

**Retrievability**—NRC regulations require that the repository be designed to preserve the option of waste retrieval should conditions require it. The DOE has established a policy that any or all of the emplaced waste can be retrieved on a reasonable schedule starting at any time in the preclosure period. The design of the Yucca Mountain disposal system gives future generations the choice of either closing and sealing the underground facility as early as allowable under NRC regulations, or keeping it open and monitoring it for a longer time period, as permitted by the NRC. The design for the repository does not preclude the option for future generations to continue ventilation and monitoring of the repository until making decisions to close the underground facility.

## 3.1 PRECLOSURE SAFETY ANALYSIS

**Preclosure Safety Analysis Methodology**—The preclosure safety analysis (PCSA) methodology examines the repository design for events that ultimately could lead to the release of radionuclides during operations and systematically examines the resulting event sequences, probabilities, and consequences involved. The initiating events include both internal events (e.g., the drop of a canister) and external events (e.g., an earthquake). Event sequences that might involve criticality are evaluated, and, if necessary, design features and procedural safety controls are implemented to ensure that criticality is prevented. The end products of the PCSA are calculated doses to worker and public groups identified in NRC regulations and a comparison to regulatory limits for maximum doses.

The identification of events involves the compilation of events that are applicable to the repository, including both internal and external events. Events with similar system response are grouped, and screening criteria are applied to eliminate the calculation of consequences for those of sufficiently low probability to be below regulatory concern. Next, event sequence diagrams are developed, portraying the actions subsequent to an initiating event. An event sequence is a series of actions or occurrences that could potentially lead to exposure of individuals to radiation. An event sequence includes one or more initiating events and associated combinations of repository system component failures, including those produced by the action or inaction of operating personnel. Different sequences that could result are evaluated to determine probabilities of occurrence of the sequence of events. Once the probabilities have been determined, the sequences can be categorized by probability, and the consequences, expressed as doses, can be calculated. The categories include those event sequences that are expected to occur one or more times before permanent closure of the repository and those more rare occurrences that are not expected to occur but are analyzed to determine what the consequences would be. Doses are calculated for workers and members of the public for the first category and for the public for the second category.

Once the doses are determined, they are compared to regulatory limits. If the doses exceed the regulatory limits, event sequence prevention or mitigation strategies are used to refine the repository design, and the event sequences are reexamined. This is an important aspect of the preclosure design and assessment strategy. It allows the DOE to change the design in order to minimize the likelihood of or to prevent an event sequence that leads to doses to workers or the public. If the doses are below the regulatory limits, the parts of the repository system that are important to safety are then identified. Special care is taken in the construction and operation of these components that are important to safety to ensure that the repository is operated safely.

The PCSA considers event sequences that are anticipated to occur. Systems are made reliable enough to prevent the event that might initiate the sequence or to reduce the severity of the consequences in case the initiating event does occur. Additionally, through the identification of potential hazards, the structures and equipment are designed to prevent undesired outcomes. For example, cranes lifting waste containers are limited in their movements to prevent the waste container from being lifted too high and hitting the walls of the structures. In the unlikely event that a waste container is breached, the structure is built to confine the radioactive material within affected areas and to filter the air through HEPA filters to capture the radioactive materials. These structures are heavily shielded, and these types of operations are performed remotely. Used filters will be handled as radioactive wastes and will be properly disposed. Overall, a defense-in-depth approach is taken. This approach (1) seeks to prevent an entire potential chain of events, (2) prevents each step in such a potential chain of events individually, and (3) prepares to effectively mitigate the consequences of each event in that potential chain.

## 3.2 RESULTS OF THE PRECLOSURE SAFETY ANALYSIS

The preclosure system safety evaluations show convincingly that the repository, if designed and operated as planned, will be safe and meet the applicable EPA standards and NRC regulations. Results of the PCSA in support of the license application show that the calculated potential doses are well below the limits allowable under the regulations. The results of the PCSA discussed below are summarized in Table 1 and represented in Figure 9.

### *Normal Operations*

The NRC has set maximum dose limits for normal operations, including limits to dose resulting from certain unexpected events that would be likely to occur during normal operations. The DOE has not identified any such unexpected events; however, as discussed below, the DOE has identified less frequent, abnormal events. The DOE has used conservative methods to evaluate potential doses such that the results overestimate the likely doses to be received during actual operations.

**On Site**—Radiation workers and onsite members of the public will receive only a small fraction of the dose limits permitted by NRC regulations. The NRC limits radiation worker and onsite public doses to the total normal operating dose and the annualized dose from any event likely to occur during normal operations. Because there is no likely event-sequence dose contribution, the NRC radiation worker limit of 5 rem per year is considerably more than the calculated dose of 1.3 rem per year as the maximum dose for a radiation worker within the geologic repository operations area. There will also be nonradiation workers that are in proximity to the repository. The NRC has set a limit of 100 mrem per year for these individuals, and it is calculated that a nonradiation worker could receive up to 78 mrem per year at the most exposed location.

Table 1. Summarized Results of Preclosure Safety Analysis

| Person Exposed | Location | Type of Exposure | NRC Limit | Calculated Dose |
|---|---|---|---|---|
| Public | Site boundary | Normal operations and expected event sequences | 15 mrem/yr | 0.05 mrem/yr |
| | | Abnormal events | 5 rem (per event) | 10 mrem |
| Radiation Worker | Within the geologic repository operations area | Normal operations and expected events sequences | 5 rem/yr | 1.3 rem/yr |
| Nonradiation worker (onsite member of the public) | Outside the repository fence, within the site boundary | Normal operations and expected event sequences | 100 mrem/yr | 10 mrem/yr (nominal) 78 mrem/yr (maximum) |
| Nevada Test Site and Nevada Test and Training Range (public) | Site boundary | Normal operations and expected event sequences | 100 mrem/yr | 0.11 mrem/yr |
| | | Abnormal events | 5 rem (per event) | 30 mrem |

**Offsite**—Normal operations associated with handling of radioactive material will contribute only a small fraction of the permitted dose limit to the public in the general environment (i.e., everywhere outside the site boundary, Nevada Test Site, and Nevada Test and Training Range). The NRC maximum limit to the public at the site boundary is 15 mrem per year. The calculated dose at the site boundary to the general environment (due entirely to normal operational releases) to a hypothetical member of the public is 0.05 mrem. The calculated dose of 0.11 mrem per year for a member of the public not in the general environment is a very small fraction of the NRC limit of 100 mrem per year.

### *Abnormal Events*

The NRC also has set maximum dose limits for abnormal events, and the DOE has identified and analyzed the consequences of infrequent, abnormal events. Because conservative methods were employed to evaluate the potential doses, the DOE believes that the results overestimate the likely doses to be received during actual operations.

**Offsite**—Even though it is possible to conclude that the need to consider certain accident events has been excluded by aspects of the design, the DOE has nonetheless considered and analyzed these potential accidents to check that systems are in place in case the unexpected happens. This involves an analysis of assumed failures in the structures and equipment and of the systems designed to control releases from such events with a greater than 1 in 10,000 chance of occurrence over the operational period. The results of these analyses show the total dose per event could be up to approximately 10 mrem. Compared to an NRC limit of 5 rem (5,000 mrem) per event, this is a small fraction of the regulatory standard.

The DOE will also implement an Emergency Response Plan, which addresses responses to accidents that may cause a radioactive material release. It is important to note, however, that it is not expected that accidents that have been categorized as likely to occur during the operational period would require a response by an offsite response organization. Despite this expectation, the DOE will be prepared so that in case there is such an event, offsite response organizations will be notified and could be mobilized.

### Comparative Doses

The exposures associated with potential releases from the repository during operations and before permanent closure are well below the range of exposures people encounter every day and accept as part of their lives. An understanding of the magnitude of these exposures can be developed by comparing the potential releases from the repository to other similar exposures people encounter every day.

Normal operations associated with handling radioactive material lead to a calculated small dose to a person at the site boundary of 0.05 to 0.11 mrem per year. This is a small fraction of the NRC allowable limit, and an even smaller fraction of naturally occurring background radiation. Doses at this low level can be found in food, such as fruits and vegetables that contain potassium. The radiation dose from eating a banana with naturally occurring radioactive potassium is about 0.01 mrem. Therefore, the dose to the public from normal operations of the repository is about the same as eating five bananas in a year. In addition, the Health Physics Society recommends against quantitative estimation of health risks below an individual dose of 5,000 mrem in one year, or a lifetime dose of 10,000 mrem in addition to background radiation. 10,000 mrem in a 70-year lifetime is equivalent to about 150 mrem per year. The conservatively estimated offsite dose from normal operations is well below this level.

The potential radiation release due to an abnormal event or accident is higher but still below the range of risk routinely accepted by the public. The results of the analyses presented in the license application show the total dose per abnormal event or accident could result in approximately a 10 to 30 mrem dose at the site boundary. Naturally occurring background radiation in the United States is in the range of from about 200 to 300 mrem per year. Many locations in the United States have background radiation 100 mrem per year higher than this average. In other words, potential additional doses to the public from an abnormal event at the repository are comparable to those associated with a choice to live in a part of the country with higher background radiation.

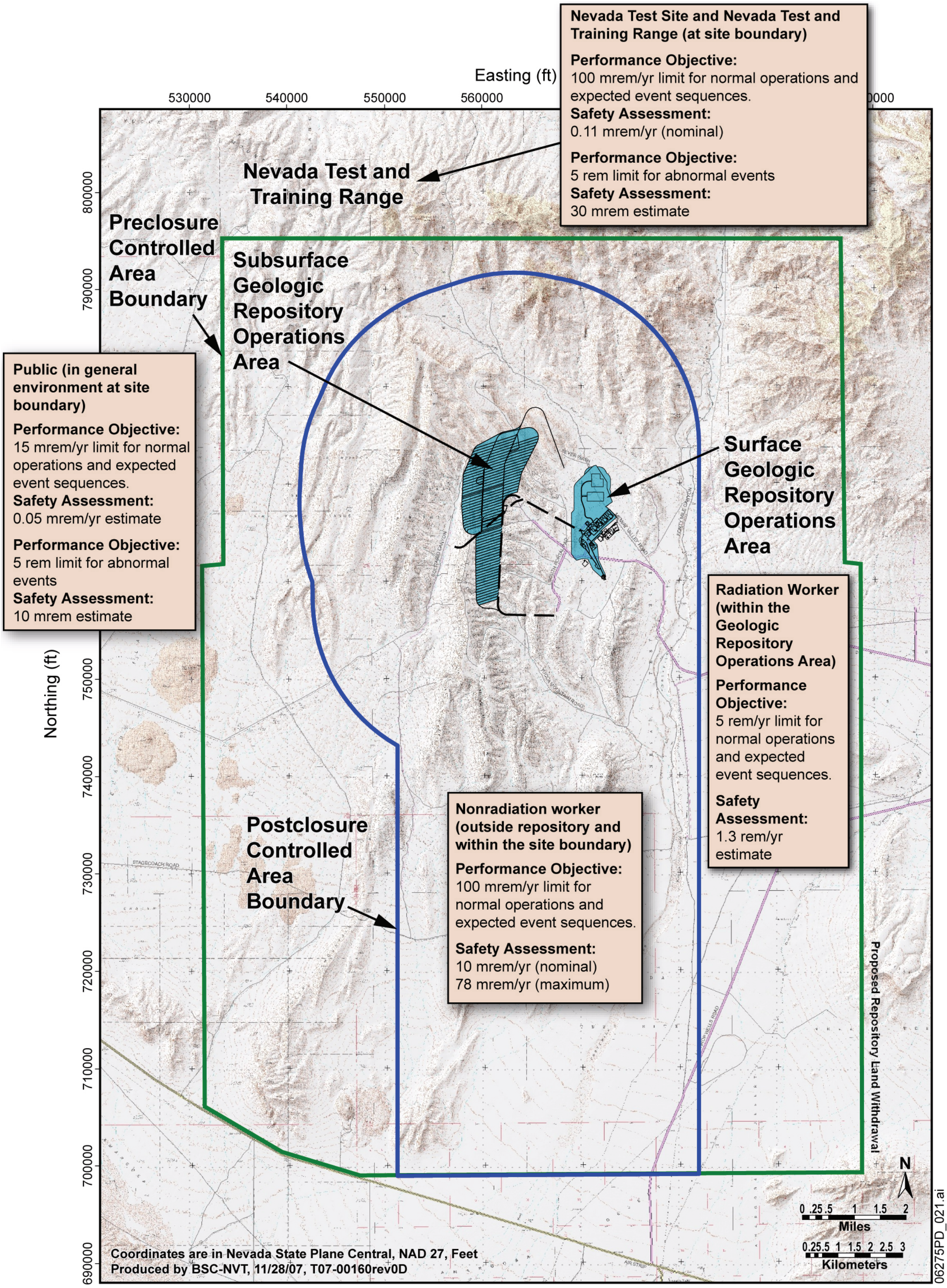



Figure 9. Summarized Results of Preclosure Safety Analysis Compared to Regulatory Performance Objectives at the Yucca Mountain Repository

# 4. Safety of the Repository after Permanent Closure

The safety of the repository at Yucca Mountain after permanent closure (postclosure) is ensured by the use of two safety principles. First, the engineered barrier system is designed so that, working in combination with the natural features of the site, potential, very distant future radiological doses to a reasonably maximally exposed individual described in the regulation are expected to be well below the limits specified by the NRC. In other words, the engineered components must be designed to take advantage of the characteristics of the natural features of the Yucca Mountain site.

> **reasonably maximally exposed individual.** A hypothetical person, defined by regulation, who is likely to receive a greater radioactive exposure than the average person in the area because of the conservative way the regulations define the lifestyle characteristics.

The second safety principle is that the geologic repository includes multiple barriers, consisting of both natural barriers and an engineered barrier system. Geologic disposal of radioactive waste is predicated on the expectation that one or more features of the geologic setting will be capable of contributing to the isolation of radioactive waste, meaning it acts as a barrier to the movement of radionuclides out of the repository. While there is an extensive geologic record ranging from thousands to millions of years, this record includes many uncertainties. In addition, there are uncertainties in the isolation capability and performance of engineered barriers over very long timeframes. These two types of uncertainties are addressed by requiring that multiple barriers make up the repository system to ensure that repository performance is not wholly dependent on a single barrier. As a result, the system is more tolerant of failures and external challenges, such as earthquakes.

## 4.1 FEATURES OF THE REPOSITORY SYSTEM CONSIDERED IN ASSESSMENTS OF LONG-TERM PERFORMANCE

The combined geologic and engineered features that make up the postclosure repository system have several attributes that are important to keeping radionuclides away from humans. Because water is the primary medium by which radionuclides could be released from the repository, the beneficial characteristics of the system primarily relate to the ability of the site and the design to prevent or limit the movement of water. The system features are described here in the order that a drop of water would encounter them as it moved from the surface to the environment where the reasonably maximally exposed individual would live.

> **capillary forces.** Forces caused by surface tension that cause liquids to be held in small-diameter pores. Capillary forces are a characteristic of unsaturated zone hydrology that cause water to be held in much the same way a sponge holds water until it is saturated. These forces limit the movement of water through the rock.

Above the repository, the important features are the nature of the site and its geologic character. The topography, rock, and soils at the surface of Yucca Mountain are the initial features that limit the movement of water into the mountain (Figure 10). Precipitation at Yucca Mountain is very low and is expected to remain low even during somewhat colder and wetter future climates associated with the likely return of glacial conditions to North America. Runoff, evaporation, and plant transpiration combine to divert water and permit only a small fraction of the already–low expected precipitation at the site to infiltrate into the mountain. The volcanic tuffs in the unsaturated zone above the repository will further reduce the movement of water through the unsaturated zone. They divert percolating water, attenuate or dampen pulses of infiltration, and limit seepage into the emplacement drift through capillary forces. The repository horizon is expected to remain well above the water table during wetter future climate conditions.

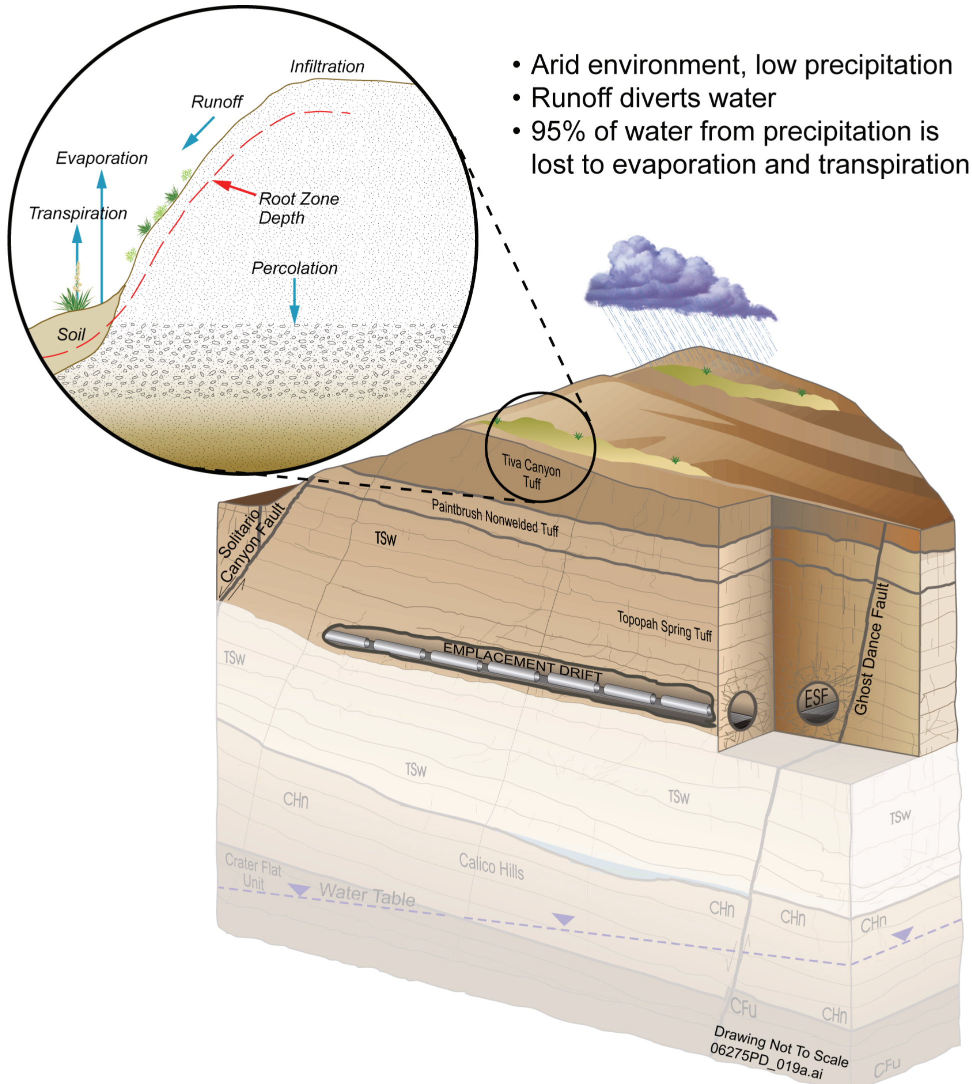



Figure 10. Features of the Repository above the Emplacement Horizon That Limit the Amount of Water That Can Contact the Waste

The features of the engineered barrier system have been designed to prevent or limit the movement of water and to prevent or substantially reduce the release of radionuclides from the waste. Figure 11 illustrates these features, which include the emplacement drift, the drip shield, the waste package, the waste form and other materials contained inside the waste package, the waste package pallet, and the drift invert. Because of capillary forces, most of the water moving in the unsaturated zone will be diverted around the emplacement drifts, and only a fraction will seep into the drifts. Structurally strong and highly corrosion-resistant titanium drip shields will prevent contact between seepage water and waste packages. These shields are expected to be intact for hundreds of thousands of years. Waste packages will be made with an outer cylinder of a highly corrosion-resistant nickel-based alloy known as Alloy 22, which will prevent any contact between water and the waste for as

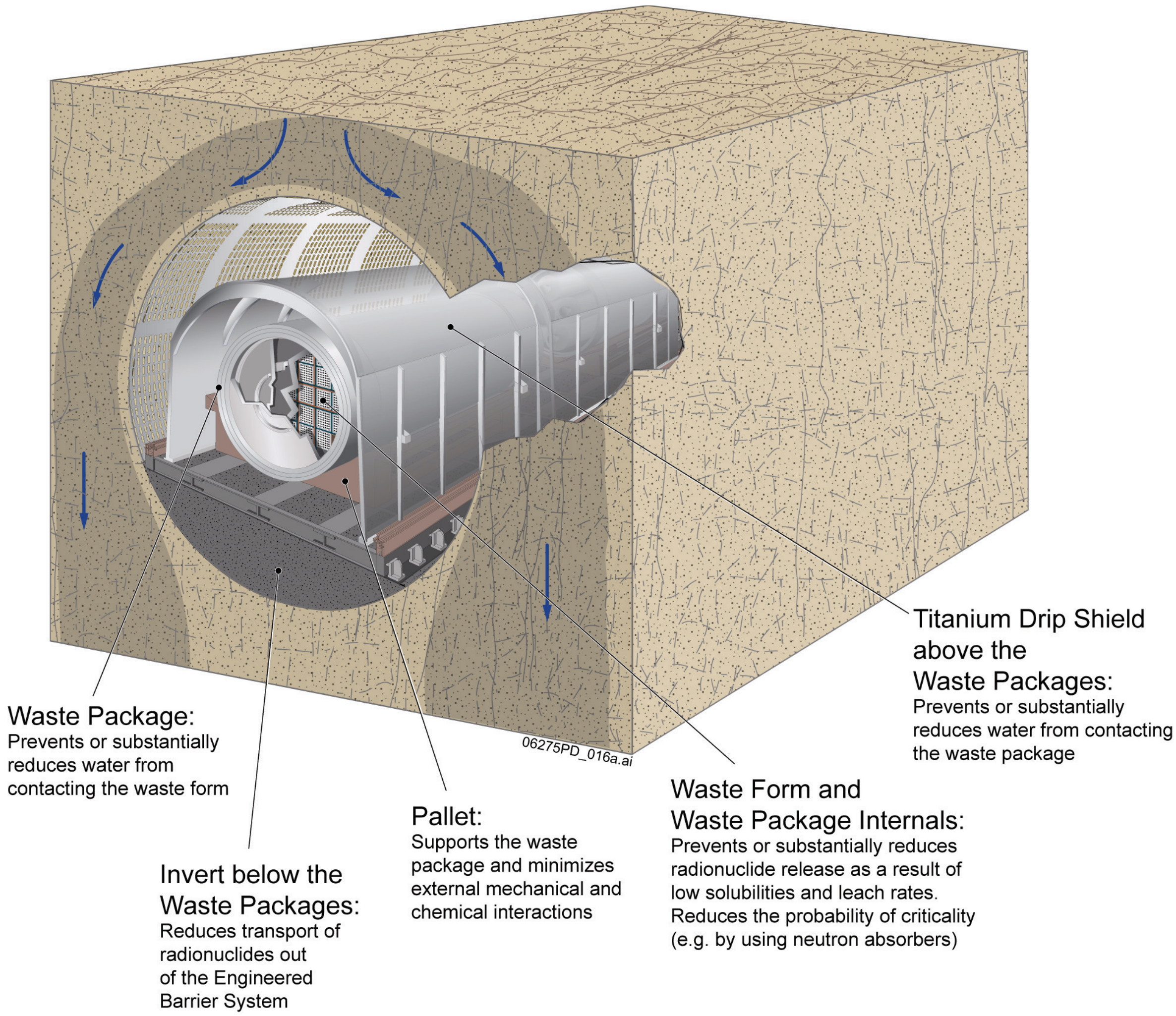



Figure 11. The Features of the Engineered Barrier System that Prevent or Limit the Movement of Water and Prevent or Substantially Reduce the Release of Radionuclides from the Waste

long as the waste packages remain intact, which is also expected to be for hundreds of thousands of years, absent unlikely seismic and igneous events. Stress corrosion cracking related to rockfall or in welds could potentially cause damage to drip shields and waste packages into thousands of years, but the size and characteristics of the cracks are not expected to allow the movement of water into the packages. Although breach of a waste package will permit the potential release of radionuclides, any such release will be impeded by the slow rate of waste form degradation. The waste forms are solid, and degradation will not begin until air and moisture contact the waste form.

**diffusion.** The spreading out of particles, such as radionuclides, as they move in water (e.g., how a drop of ink spreads in water).

Significant release of radionuclides can only occur if they are dissolved in water or attached to very small particles called colloids and if there are continuous liquid pathways into and leading out of the waste package through the invert and into the surrounding rock. Some minor gaseous releases will also occur, but they will disperse rapidly. Continuous pathways of flowing liquid water are not expected in the unsaturated repository environment, although limited diffusive transport may occur.

The amount of water in contact with the waste form is expected to be limited to a thin film on the waste form surface. The waste form will limit radionuclide release rates because most of the radionuclides are not very soluble in the water due to chemical conditions in the mountain. Both SNF and HLW glass will degrade and dissolve slowly in the repository environment.

**solubility.** A material is soluble if it dissolves readily in liquids that contact it. Solubility is controlled by chemistry and can be limited by the amount of material already dissolved.

**sorption.** Attraction of a radionuclide to an object, such as a molecule becoming attached to it.

Analogue evidence indicates that glass, metals, and ceramic materials may be preserved for thousands of years in the unsaturated zone underground. For example, there is volcanic glass in some Yucca Mountain rock that has been there for more than 10 million years. Transport of radionuclides by water out of the engineered features of the repository will be further limited due to the small volumes of water and limited number of flow paths present in the unsaturated zone. The transport of many dissolved radionuclides, including those that are the greatest part of the total inventory of radionuclides, will be further retarded by sorption on iron corrosion products that form within the waste package once degradation begins. Waste package internal structures will begin to corrode before the waste form. Radionuclides transported in the water can also be trapped and retarded by sorption onto corrosion products.

Unlike other hazardous materials, the danger associated with radioactive materials naturally diminishes over time through a process known as radioactive decay. The half lives of the majority of the radionuclides stored at the repository are fairly short. About 1,000 years after repository closure, little more than 18% of the original amount of radioactivity emplaced in the repository would remain, and about 6% would remain after 10,000 years. Imagining the initial quantity of radioactivity emplaced in the repository as 1,500 marbles, natural radioactive decay would leave 270 marbles after 1,000 years and only 90 marbles after 10,000 years. By 100,000 years, there would only be eight marbles left. Finally, after 1 million years, just one marble out of the original 1,500 would remain—the amount of the original radioactivity remaining would be about 0.07%, and about 99.93% of the radioactivity originally placed in the repository would have decayed.

**half life.** The time it takes for a substance to lose one-half of its radioactivity.

Below the repository, the geologic layers are important features along the potential transport pathways from the repository to the environment. These include the unsaturated and saturated volcanic rocks immediately below and south of the repository, as well as alluvial deposits in the Amargosa Valley that will be encountered along the flow path approximately 6 to 9 miles south of Yucca Mountain (Figure 12). Any radionuclides that migrate down through the unsaturated zone to the water table must be transported through the saturated zone before they can reach the accessible environment. The transport of radionuclides will be limited by the rate at which water flows. In addition, several processes will cause the movement of radionuclides to be slower than the rate of movement of the water. These include diffusion into the porous matrix of fractured volcanic rocks, sorption of radionuclides onto mineral surfaces in both fractures and the porous rock matrix, and precipitation of minerals as chemical conditions change along the flow path.

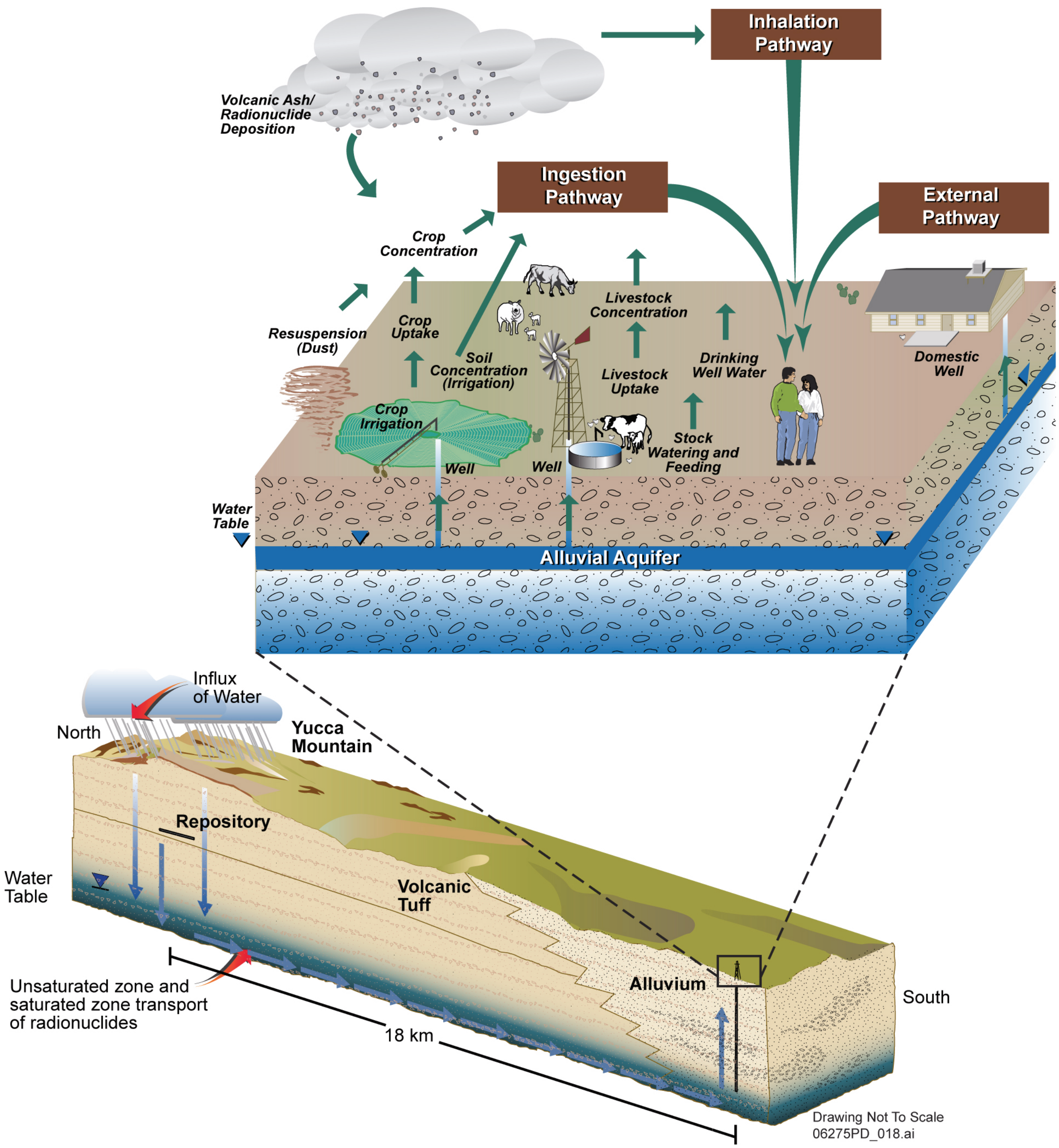



Figure 12. Location and Characteristics of the Reasonably Maximally Exposed Individual and the Features of the Natural System below the Repository That Limit Movement of Radionuclides to That Location

The final portion of the movement of water is to the humans that could use it. The reasonably maximally exposed individual is a hypothetical individual defined by regulations to exist in the accessible environment who draws water from a well centered in the potential contaminated groundwater coming from Yucca Mountain (Figure 12). The reasonably maximally exposed individual is defined by regulation in a way that makes sure that this person is more exposed than can be expected for a real individual near the same location. This individual may be exposed to radiation from contaminated water in a number of ways, all of which are calculated.

## 4.2 TOTAL SYSTEM PERFORMANCE ASSESSMENT

The postclosure repository system is, by its nature, a passive system that requires no external actions or activities in order to perform its function; indeed, no human intervention is planned or necessary after closure. Given the time periods over which the repository must perform, neither automated nor active systems can be relied upon to reduce risk. Because the natural features important to isolating wastes are existing elements of the site and system, they must be used as they are. Safety after permanent closure (i.e., the postclosure period) is assessed by examining the features, events, and processes that could affect long-term performance. Features, events, and processes are the specific conditions or attributes of the geologic setting; the degradation, deterioration, or alteration processes of engineered barriers; and the interactions between the natural and engineered features that might affect performance of the geologic repository. The assessment method used is called total system performance assessment, and its approach is internationally accepted. For Yucca Mountain, the specific way in which it was performed is defined by the NRC regulations.

**total system performance assessment.** A risk assessment that quantitatively estimates how the proposed Yucca Mountain disposal system will perform in the future under the influence of specific features, events, and processes, incorporating uncertainty in the models and data.

**Total System Performance Assessment Methodology**—Total system performance assessment (TSPA) is a calculational tool that provides quantitative estimates of the long-term performance of the total repository system over a range of possible conditions using computer models that are based on site data and materials-testing data and accepted principles of physics and chemistry. A TSPA compiles analytic models of the engineered and natural system processes acting at the repository into an overall computer model of the repository and surrounding environment to assess overall repository performance. With the TSPA model, the DOE can estimate releases of radionuclides from the repository under a range of conditions over many thousands of years and estimate the potential doses to persons.

The TSPA models are usually referred to as abstracted models and involve the extraction of essential information from large quantities of data. An abstracted model in a TSPA may take the form of something as simple as a table of values that were calculated using a complex computer model or of a fully three-dimensional computer simulation. These are the models used to evaluate system performance and estimate the likelihood that the performance will comply with regulations and ensure long-term safety. The responses of the total system extend over periods beyond those for which data have been or can be obtained; the TSPA models address this by treating the data as uncertain and evaluating the results in a probabilistic manner.

TSPA model development includes the compilation of a list of all possible features, events, and processes (FEPs) that could apply to the behavior of the system. The existence of a fault is an example of a feature. An example of an event is a seismic event (e.g., earthquake), and an example of a process is the gradual degradation of the waste package wall by general corrosion. The DOE used various types of analyses to determine the FEPs it should include in the modeling. The selected features, events, and processes are assembled into scenario classes, which describe expected situations and disruptive situations, such as seismicity and volcanism.

Estimates of doses are calculated using a probabilistic approach called Monte Carlo sampling. A value is selected for each of the uncertain data inputs, and the repository performance is simulated for 10,000 and 1 million years. This is repeated 300 times, and the maximum of the mean (average) value is identified for the 10,000-year performance standard. For the 1-million-year performance standard, the maximum of the median value is identified.

**Model Corroboration**—Confidence is also enhanced if differences in results are properly understood when there are independent evaluations of the same system. In 2002, an international group of experts was brought in to review the TSPA of that time. Their finding was that this assessment represented a competent modeling effort in keeping with international practice. Twenty-seven recommendations were made to improve the assessment, all of which have been addressed. Suggestions by several other external expert reviews have resulted in numerous improvements in the model.

In keeping with the requirements to provide a basis for confidence in the models used in TSPA, numerous sensitivity, uncertainty, and insight analyses were performed to enhance understanding of the models and to verify that what is calculated provides confidence from the standpoint of how the system ought to behave in response to changes. Insight analyses were single-realization analyses that focused on what appear to be outliers in the cluster of results from hundreds of probabilistic analyses. Knowing what combination of factors caused that outlier and understanding whether or not it makes sense from a scientific point of view further enhances confidence in the model.

There have been other quantitative models and evaluations of the repository system's potential safety. The DOE evaluated the differences in outcomes and understands them, adding confidence to its own modeling approaches at several levels. One example of a TSPA comparison done independently of DOE is the system analyses produced by the Electric Power Research Institute, using its independently developed model and software, IMARC. This comparison suggested that, to the degree that the Electric Power Research Institute approach may be more realistic, the DOE Yucca Mountain repository TSPA is conservative in that it likely overestimates dose projections. Other methods of evaluating the credibility of modeling results include a comparison to a simplified DOE TSPA analysis that was performed independently from the main TSPA effort. Another modeling effort involved removing some key conservatisms in a performance margin analysis. Each of these modeling efforts produced comparable results.

## 4.3 RESULTS OF THE POSTCLOSURE TOTAL SYSTEM PERFORMANCE ASSESSMENT

The postclosure system safety evaluations show convincingly that the repository is safe and meets the applicable EPA standards and NRC regulations. The regulations specify several measures for addressing the consequences of a repository at Yucca Mountain: radioactivity doses to humans and groundwater radioactivity content. The regulations prescribe the method for calculating dose to a hypothetical future human being in Amargosa Valley known as the reasonably maximally exposed individual. This hypothetical future individual is defined in such a way as to provide a conservative estimate of potential doses that could result from exposure to radionuclides carried from the repository in groundwater. Any real person living in the region would receive considerably less dose. The reasonably maximally exposed individual is specified to live approximately 11 miles south of the proposed repository. Summarized results for the TSPA are presented in Tables 2 and 3 and discussed in the text that follows.

Table 2. Postclosure Performance Results for the Individual Protection Standard and Human Intrusion Standard

| | **Mean** | **Median** | **95th Percentile** |
|---|---|---|---|
| **Individual Protection Standard** | No more than 15 mrem | No more than 350 mrem[a] | None (95th percentile is provided here for comparison only) |
| First 10,000 years | 0.24 mrem | | 0.67 mrem |
| Time of occurrence | 10,000 years | | 10,000 years |
| Post-10,000 years[b] | | 0.9 mrem | 9.1 mrem |
| Time of occurrence | | ~800,000 years | 1,000,000 years |
| **Human Intrusion Standard** | | No more than 350 mrem[a] | |
| Post-10,000 years[b] | | 0.01 mrem | |
| Time of occurrence | | ~202,000 years | |

NOTE: [a]Proposed
[b]Within the proposed period of geologic stability, defined as 1 million years.

Table 3. Postclosure Performance Results for the Groundwater Protection Standard

| | **Combined $^{226}Ra$ and $^{228}Ra$ Concentration** | **Gross Alpha Activity Concentration** | **Dose from Combined Beta- and Photon-Emitting Radionuclides** |
|---|---|---|---|
| **Groundwater Protection Standard:** Limit for Activity Concentration or Annual Dose | 5 pCi/L | 15 pCi/L | 4 mrem |
| **Performance Results:** Projected Maximum Mean Activity Concentration or Annual Dose | $<10^{-6}$ pCi/L | $10^{-4}$ pCi/L | Whole body: ~0.06 mrem<br>Thyroid: ~0.26 mrem |
| Natural Background Level | 0.5 pCi/L | 0.5 pCi/L | Background level excluded in regulatory requirement |

The NRC regulations specify a maximum mean allowable annual radiological dose to the reasonably maximally exposed individual, for all scenarios combined (that is, including the effects of low probability events such as volcanism and seismicity) of no more than 15 mrem per year for the first 10,000 years. The mean value of the annual estimated dose to the reasonably maximally exposed individual is 0.24 mrem. Even if one considered the 95th percentile (95 out of every 100 simulations resulted in a dose level lower than this number), the value is 0.67 mrem. Both of these numbers are only a small fraction of the allowable limit. Proposed EPA standards and NRC regulations also specify a dose limit for the time from 10,000 years after closure through the period of geologic stability (defined as 1 million years). The regulations specify a maximum median allowable annual radiological dose to the reasonably maximally exposed individual, for all scenarios combined (i.e., including the effects of low probability events such as volcanism and seismicity) of no more than 350 mrem for this time period. The calculated median value of the annual estimated dose to the reasonably maximally exposed individual for all scenarios combined is 0.96 mrem. The 95th percentile value is 9.1 mrem. These numbers are an extremely small percentage of the allowable limit. Analyses against the groundwater protection and human intrusion standards result in comparable margins.

As noted, the reasonably maximally exposed individual is a hypothetical person defined in such a way to maximize dose to potential releases from the repository. People living in the Amargosa Valley would receive considerably less exposure because no real individual would exhibit all of the characteristics of the reasonably maximally exposed individual. People living farther from Yucca Mountain would be expected to receive even less exposure. Yucca Mountain is located in a closed groundwater basin, which ensures that, unless major geologic changes occurred, the radionuclides could not leave the basin.

### Comparative Doses

The potential releases from the repository after permanent closure are also well below the ranges of exposures people encounter every day and accept as part of their lives. As previously noted, naturally occurring background radiation in the United States is in the range of from about 200 to 300 mrem per year. Many locations in the United States have background radiation 100 mrem per year higher than this. The Health Physics Society recommends against quantitative estimation of health risks below an individual dose of 5,000 mrem in 1 year or a lifetime dose of 10,000 mrem in addition to background radiation. A dose of 10,000 mrem over a 70-year lifetime is equivalent to about 150 mrem per year.

The estimated annual doses from the repository to the reasonably maximally exposed individual for both the 10,000-year and 1-million-year period are lower than 1 mrem. This is about the same radiation dose that is received in a two-hour flight on an airplane or from watching a color television over a year. This is a fraction of a percent of naturally occurring background radiation. The estimated 95th percentile level (i.e., the value at which 95% of the calculated doses are below this level) annual doses for the 1-million-year period is lower than 10 mrem. A comparable radiation risk is that received from a chest x-ray. The maximum calculated annual dose level is about 40 mrem. This reflects the extreme values of the parameter distributions. Comparable radiation risks are at a level of dose significantly less than that received annually by an airline flight crew. These are very small percentages of the naturally occurring background radiation, well below the variability across the United States and are not likely to lead to a significant increase in the risk of cancer. It is also important to note that these potential doses are calculated for the reasonably maximally exposed individual and include very low probability disruptive events (e.g., a volcano erupting through the repository). The actual doses to a real individual would be significantly lower, at a level not expected to meaningfully contribute to an annual dose already received from background radiation.

### Confidence in the Long-Term Safety Evaluations

The estimated safety consequences shown are not predictions but are cautious and reasonable estimates of potential future performance. Nations with nuclear power programs are planning to pursue geologic disposal whether or not they are planning to recycle their SNF. Every nation actively involved in planning, finding a site for, or licensing a repository has done calculations broadly similar in scope to the TSPA performed by the DOE.

The NRC requires performance assessments to provide the information needed to make an informed licensing decision. Uncertainties are, however, inherent in evaluating a first of a kind facility like the repository and in estimating system performance over very long time periods (i.e., many tens of thousands of years). Thus, requirements are included to ensure that uncertainties inherent in any performance assessment are thoroughly articulated and evaluated. In addition, the DOE is required to show that all available, pertinent information has been taken into account and analyzed as a corroboration of the concepts and approach involved in the estimation of long-term system performance.

**Natural Analogue Studies**—Computer models show how a repository would most likely respond to changing conditions over a vast expanse of time, but there is no real way to test directly to see if events actually unfold as predicted. There are, however, examples and analogues of the kinds of climatic, geologic, and hydrologic processes that could affect repository performance. Scientists have studied information pertaining to different analogue sites throughout the world to gain a better understanding of the long-term processes that are relevant to Yucca Mountain.

By studying the past climates in an area, scientists can project the likely future climates. For example, sedimentary deposits in a dried lakebed at Owens Lake, California (about 100 miles west of Yucca Mountain) provide a nearly 425,000-year record of past climates in the region. This information, along with information from other climate analogues such as the 500,000-year record obtained from cores taken from the walls of a cave known as Devils Hole near Yucca Mountain, helps corroborate estimates of precipitation levels and atmospheric temperatures in the past, which, when coupled with information from the earth's orbit, can allow prediction of future climate states.

Scientists have also analyzed water movement in an ancient underground city in Kaymakli, Turkey (second century AD). The climate and type of rock are similar to those found at Yucca Mountain. In studying the Turkish site, scientists have observed very little water seeping into the deep underground excavations. Researchers believe that caves containing prehistoric paintings, such as those found in the Chauvet Cave in southern France, provide excellent natural analogues for the water flow at Yucca Mountain. The 30,000-year-old paintings in these caves were made with oxides of iron and small amounts of manganese, as well as clay, charcoal, and silica. None of these materials would survive long in the presence of abundant water. Yet many cave paintings have survived in locations far more humid, and with more than three times the rainfall than Yucca Mountain. Those paintings survived because water tends to flow around caves and tunnels, not into them, in part because of the comparative size of the different openings. In unsaturated rock, what little water is available in the pores and fractures has a tendency to remain there rather than flow into larger openings, such as caves or tunnels. These analogue studies suggest that seepage into repository tunnels will be minimal.

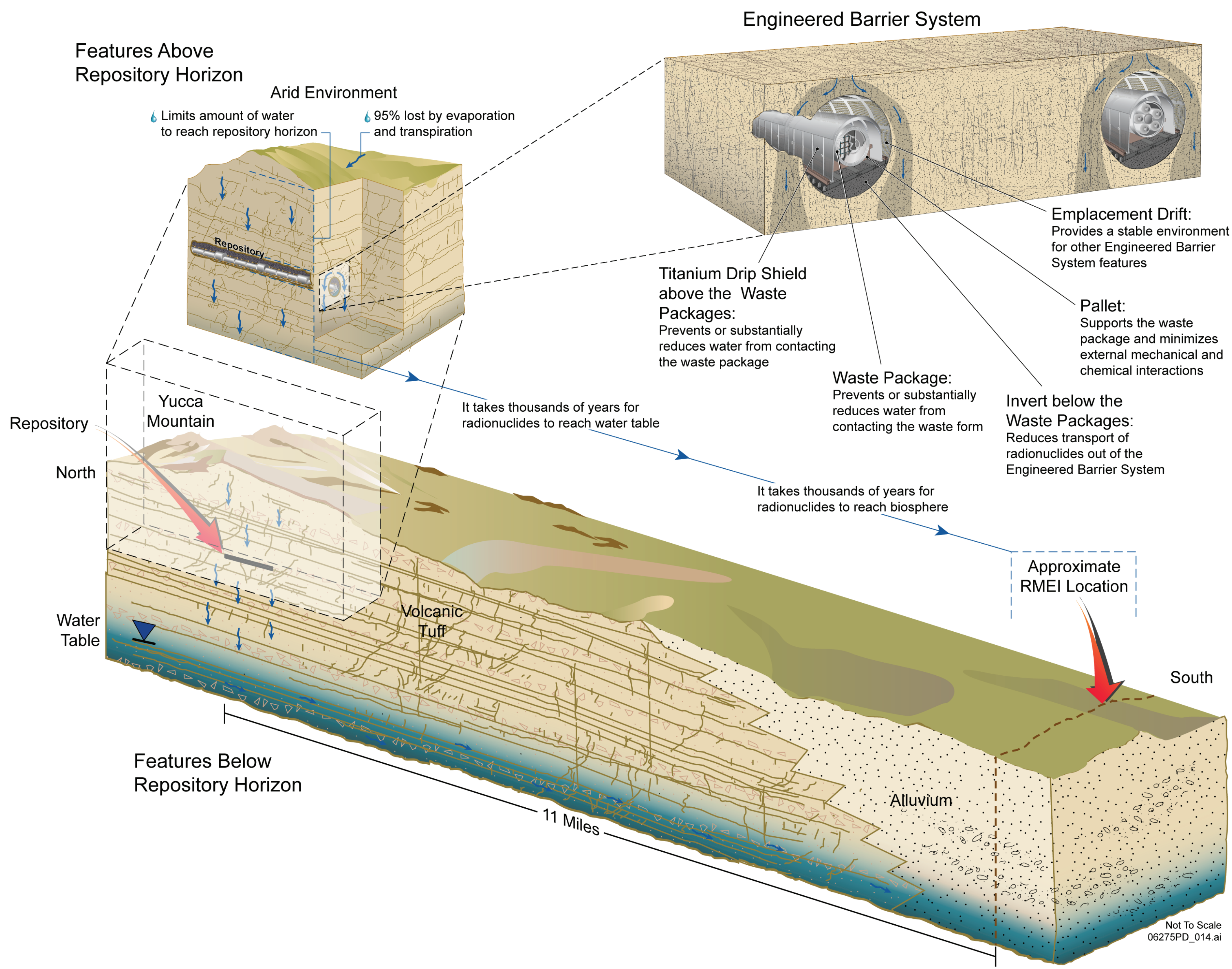
An important analogue site is a natural uranium deposit at Peña Blanca, Mexico, where the climate and rock are very similar to Yucca Mountain. The studies at this site focused on the migration of naturally occurring radioactive particles over millions of years. In these studies, scientists have observed that the particles migrated only a few yards along major fractures in the rock. The uranium deposits at Peña Blanca appear to have changed over millions of years in many of the same ways scientists expect that spent fuel rods would change within a repository at Yucca Mountain. Studies indicate radioactive particles similar to those that would exist in a repository at Yucca Mountain moved only a few yards from the ore deposit and in very low quantities.

These and other studies are reported in the technical documents that support the license application, and in total they support a finding that there is a basis for having confidence in the results of the TSPA—sufficient confidence, the DOE believes, to support a decision to allow the repository project to move into its next phase: construction. Scientific studies will continue during construction and operations, and safety evaluations will be updated at each of the major decision points and at any other time as new information becomes available and needs to be evaluated in terms of system performance implications. In addition, the entire systems will be monitored until permanent closure, and following closure of the repository, the site will continue to be monitored for continued long-term scientific and safety evaluations.

# 5. Conclusions

Technical analyses, based on approaches that are accepted internationally, provide the rationale for DOE conclusions that the repository can be built and operated safely and that the repository system will protect people far into the future. The analyses have been independently reviewed by experts, and the successive versions of the numerical models have benefited from constructive suggestions for improvement. The repository construction, operation, and performance are subject to oversight by independent regulatory agencies, and the DOE cannot construct the repository and begin operations unless the NRC finds that the repository can be operated safely and that it will protect humans far into the future. Those findings will be developed in hearings on the license application that will be open to the public and in which those who oppose the repository will have a full and fair opportunity to present any contrary evidence. The licensing hearing will be a rigorous in-depth review of the scientific and engineering support for DOE conclusions that the repository can be constructed and operated safely and will protect people far into the future, as required by EPA standards and NRC regulations.

In summary, the analyses detailed by the license application meet the applicable standards promulgated or proposed by the NRC for the construction, operation, and closure of a geologic repository at Yucca Mountain. The DOE has a valid basis for asserting that such analyses demonstrate this position. The DOE welcomes scrutiny of the license application as an opportunity to demonstrate the soundness of the science and design that underlie DOE's application to construct the repository. If the NRC eventually grants the DOE the authority to construct and operate the repository, the public can have full confidence that the repository is based on sound science and engineering and that the nation's inventory of SNF and HLW will be disposed of without unreasonable risk to the health and safety of the public.



Engineered Barrier System
Features Above
Repository Horizon
Arid Environment
Limits amount of water
to reach repository horizon
95% lost by evaporation
and transpiration
Repository
Emplacement Drift:
Provides a stable environment
for other Engineered Barrier
System features
Titanium Drip Shield
above the Waste
Packages:
Prevents or substantially
reduces water from contacting
the waste package
Pallet:
Supports the waste
package and minimizes
external mechanical and
chemical interactions
Waste Package:
Prevents or substantially
reduces water from
contacting the waste form
Invert below the
Waste Packages:
Reduces transport of
radionuclides out of the
Engineered Barrier System
It takes thousands of years for
radionuclides to reach water table
It takes thousands of years for
radionuclides to reach biosphere
Yucca
Mountain
Repository
North
Approximate
RMEI Location
South
Volcanic
Tuff
Water
Table
Alluvium
Features Below
Repository Horizon
11 Miles
Not To Scale
06275PD_014.ai

U.S. Department of Energy
Office of Civilian Radioactive
Waste Management

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