U.S. Nuclear Waste Technical Review Board

Report to The U.S. Congress and The Secretary of Energy

March 1, 2006–December 31, 2007

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The Board appreciates the assistance of DOE in providing many of the graphics used in this report.

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201

August 2008

The Honorable Nancy P. Pelosi
Speaker of the House
United States House of Representatives
Washington, DC 20515

The Honorable Robert C. Byrd
President Pro Tempore
United States Senate
Washington, DC 20510

The Honorable Samuel W. Bodman
Secretary
U.S. Department of Energy
Washington, DC 20585

Dear Speaker Pelosi, Senator Byrd, and Secretary Bodman:

The U.S. Nuclear Waste Technical Review Board submits this *Report to The U.S. Congress and The Secretary of Energy* in accordance with provisions of the Nuclear Waste Policy Amendments Act of 1987, Public Law 100-203, which directs the Board to report its findings and recommendations to Congress and the Secretary of Energy at least two times each year.

Congress created the Board to evaluate the technical and scientific validity of activities undertaken by the Secretary of Energy related to implementing the Nuclear Waste Policy Act of 1982. This report summarizes the Board's major activities from March 1, 2006, through December 31, 2007. The report also includes a discussion of the Board's technical evaluation of work undertaken by the Department of Energy (DOE) during that period related to disposing of, packaging, and transporting spent nuclear fuel and high-level radioactive waste. The report appendices include Board correspondence, congressional testimony, Board performance plans and evaluations, and related materials.

The Board hopes that this information will provide a useful technical context for addressing issues related to managing the nation's spent nuclear fuel and high-level radioactive waste.

Sincerely,
{Signed by}

B. John Garrick
Chairman

U.S. Nuclear Waste Technical Review Board

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Executive Summary

The U.S. Nuclear Waste Technical Review Board was established by Congress in the Nuclear Waste Policy Amendments Act. The Act requires the Board to evaluate the technical and scientific validity of the work undertaken by the U.S. Department of Energy's (DOE) Yucca Mountain Project to develop a geologic repository system for disposing of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) produced by the nation's nuclear defense complex and commercial nuclear power plants. The results of the Board's evaluation, along with its recommendations, must be reported at least twice yearly to Congress and to the Secretary of Energy.

Between March 1, 2006, and December 31, 2007, the period covered by this report, the Board focused its evaluation on five critical technical issues dealing with preclosure operations of the waste management system and on six critical technical issues dealing with postclosure performance of the proposed Yucca Mountain repository. The Board also explored in depth the crosscutting issue of thermal management. The Board's views on these issues are summarized below and are explained in greater detail in the body of this report.

The Context of the Board's Review

Over the last two years, the Office of Civilian Radioactive Waste Management (OCRWM) in DOE has made considerable progress in restructuring its repository development efforts. OCRWM reorganized its scientific work on the repository, centralizing it at Sandia National Laboratories (SNL). It redesigned completely the proposed repository's surface facilities, in part to minimize handling of bare commercial SNF. Key to that redesign was the Project's decision that most commercial SNF would be sent to the repository in standardized sealed transportation-aging-disposal (TAD) canisters, which would be loaded at utility sites. OCRWM also finalized the performance specification for the TAD canister system and initiated a procurement for detailed designs.

The Project successfully met key milestones that would enable it to fulfill a commitment to Congress to submit a License Application (LA) for constructing a repository to the U.S. Nuclear Regulatory Commission (NRC) no later than June 30, 2008. DOE published a

draft environmental impact statement for evaluating changes in the repository program that had taken place since 2002. It released two draft environmental impact statements to support decisions related to the construction of a rail line and the operation of a railroad in Nevada. Finally, it certified its document collection that now resides electronically on NRC's Licensing Support Network, which was established to facilitate the discovery process in anticipation of a hearing on the LA. The Board considers all of these achievements significant accomplishments for the program. (On June 3, 2008, after the period covered by this report, DOE submitted an LA to NRC.)

Preclosure Operations of the Waste Management System

Transportation-Aging-Disposal Canister Concept

The Board has followed closely the TAD canister development process and commented on it in a series of letters to the Project. The Board agrees that many of the advantages that OCRWM envisions for the TAD canister concept might be realized. But the Board also notes that hurdles must be overcome before the potential advantages of a canister-based system can be secured. The Board recommends that DOE carry out comprehensive analyses to understand better the implications of not achieving the 90 percent TAD canister utilization rate that has been assumed by the Project. Furthermore, the Board continues to encourage DOE to study actively all possible options for dealing with commercial SNF that already has been loaded in dual-purpose canisters—including direct disposal.

Surface Facility Operations

The Project's decision to adopt the TAD canister concept catalyzed its redesign of the surface facilities at the proposed repository. Both initiatives are responsive to the Board's concerns about the number of times that bare commercial SNF assemblies would have to be handled at Yucca Mountain.

Although the facility redesign effort addressed very well the issue of handling bare fuel, the Board believes that other issues still remain unresolved. For example, the Board thinks that the Project's preliminary estimates of throughput may be overly optimistic. The Board recommends that OCRWM represent throughput processes more realistically and evaluate measures that could improve throughput, including increasing the capacity of the Waste Handling Facility (WHF) pool to allow parallel removal and transfer of fuel in dual-purpose casks and increasing the number of welding stations in the WHF and the Canister Receipt and Closure Facility to eliminate potential choke points.

Preclosure Safety Analysis

The Project is required to prepare a Preclosure Safety Analysis (PCSA) of its surface and subsurface operations as part of the LA. As of the end of 2007, that effort had not yet been completed. The Board expressed its concerns about the Project's decision to develop a PCSA that combines deterministic and risk-informed probabilistic methodologies. Based on what the Board has seen, it is unclear at this point how OCRWM intends to address the uncertainties associated with the aggregation of risk across different activities.

Transportation

The Board remains concerned that the Project does not fully appreciate the ramifications of potential delays in the construction of a rail line to Yucca Mountain or the possibility that a rail line may never be built. DOE's declaration that the TAD canister would be the centerpiece of its waste management strategy implicitly made the Project dependent on the existence of a Yucca Mountain rail line. Given that no such line exists today and that construction of such a line may encounter significant challenges, the absence of a workable alternative for such a vulnerability is not prudent. Therefore, the Board believes that the Project should immediately and aggressively pursue a contingency plan in which the truck mode (heavy-haul or off-road) is considered within Nevada.

Waste Management System Integration

The Board conceives of a waste management system composed of four elements: waste acceptance, transportation, surface operations, and subsurface operations. It is imperative that the system be analyzed and evaluated as an integrated whole. One potentially important integrating methodology is OCRWM's Total System Model (TSM). The Board strongly supports the use of TSM, maintaining that it can play a valuable role in analyzing the operational interdependencies of the waste management system and the utility of the TAD canister concept. Nonetheless, the Board recommends several areas where the use of TSM could be strengthened, including adding a capability to evaluate "upset" conditions, such as equipment breakdowns, and to evaluate the effects of alternative thermal management strategies.

Postclosure Performance of the Proposed Repository System

Extensive field and laboratory studies as well as detailed analyses were undertaken by OCRWM to develop both qualitative and quantitative estimates of how a repository might perform hundreds of thousands of years into the future. The Project's efforts to develop those estimates have become increasingly sophisticated and evidence-based. The Board commends OCRWM for undertaking a broad suite of investigations, which often break new scientific and technical ground.

In evaluating the scientific and technical bases for the Project's estimates, the Board has identified six areas where improvements and enhancements still can be made. Although some additional work would be required to address Board concerns, the Board does not believe—with the possible exception of realistic waste degradation modeling—that this work would be especially difficult to carry out. In any event, completing this work could enhance the confidence that can be placed in the Project's performance estimates.

Infiltration Estimates

Water is the primary vehicle by which the radionuclides in the SNF and HLW might be transported out of the repository. Responding to a commitment made to Congress, the Board evaluated the technical basis underlying two different estimates of how much water infiltrates below the root zone at Yucca Mountain. One set of estimates was developed by the U.S. Geological Survey (USGS), the other by SNL.

The USGS estimates of infiltration are based on an extensive suite of site-specific data and are consistent with multiple independent lines of evidence. Furthermore, the Board's opinion is that the USGS program produced valuable results that are important for understanding the mountain hydrology and for building confidence in the estimated performance of the proposed repository.

SNL developed its estimates using a model that does not include consideration of all available site-specific data used by USGS, such as soil depth and soil and rock hydraulic parameters. Consequently, the SNL estimates of present-day infiltration at Yucca Mountain are approximately three times higher than the USGS estimates, and the SNL estimates are less consistent with independent lines of evidence, including measurements of temperature and salt (chloride) concentrations at depth within Yucca Mountain. However, the SNL approach has a more complete representation of uncertainties associated with relevant physical parameters—a methodological advantage over the USGS approach.

Infiltration estimates are used as input for OCRWM's Total System Performance Assessment (TSPA), a complex computer model designed to project the performance of the proposed repository into the far future. To make the SNL estimates compatible with observed site-specific data supporting related models in TSPA, the Project uses a statistical process that preferentially considers the lower end of the range of SNL infiltration estimates. As used by the Project, this statistical modification of the infiltration estimates does not have a strong technical basis, and thus, the Board does not endorse the use of the statistically modified SNL infiltration estimates in TSPA.

The Board believes that all available data should be used in assessing infiltration estimates, as was done in the USGS estimates. The Project also should continue its rigorous treatment of uncertainties, as was done by SNL.

Deliquescence-Induced Localized Corrosion

The outer shell of the Project's currently designed waste package is made up of Alloy 22, a corrosion-resistant nickel-based metal. Over the last several years, the Board has recommended that OCRWM examine whether salts found in the dust that would accumulate during tunnel ventilation could, by deliquescence at high temperatures, form brines that might initiate and promote localized corrosion. The Project has decided to exclude or "screen out" the process of deliquescence-induced localized corrosion from its TSPA.

After intensive review, including a two-day technical workshop in which scientists from a wide range of interested organizations participated, the Board set forth conditions that must be satisfied to support a technically defensible decision to screen out, based on low consequences, deliquescence-induced localized corrosion during the thermal pulse. Inhibitive nitrate-to-chloride ratios must be determined for the entire range of temperatures over which deliquescent brines may occur on waste package surfaces. The preferential migration of nitrate ions into a crevice on the waste package must be sufficient to maintain nitrate-to-chloride ratios that are inhibitive. The Board strongly recommends that OCRWM conduct investigations for determining whether these two conditions are satisfied.

Further, the Board notes that the dust settling on waste package surfaces during preclosure ventilation would contain significant amounts of organic materials and that reactions between the materials and nitrate in the dust could affect the amount of nitrate available to inhibit corrosion. The Board believes that the Project also should analyze the effects of

the full range of factors (e.g., organics in dust, acid-gas devolatilization, and radiolysis) that could influence whether inhibitive nitrate-to-chloride ratios persist under postclosure repository conditions.

Development of a Safety Case

For more than a decade, the Board has held that it is important for OCRWM to develop a structured presentation of the evidence, analyses, and lines of reasoning that can build confidence in the conclusions derived from TSPA. This set of arguments constitutes what is commonly called a "safety case." The Board endorses the Project's effort to develop a safety case, noting, for example, that the use of natural analogues can provide excellent tests of prevailing conceptual and numerical models of radionuclide transport and isolation.

Waste Degradation and Radionuclide Transport

If the waste package fails, the waste, in its various forms, may begin to degrade. The degradation process is complex, and the fate of the radionuclides in the waste is uncertain. The Project's implementation of TSPA therefore uses conservative assumptions about radionuclide transport that may often be unrealistic. On several occasions, the Board has observed that obtaining a better fundamental understanding of the entire transport process remains a productive avenue for additional scientific investigation.

Although the variables affecting radionuclide transport, such as temperature, pH, redox state, and ionic strength, can be enumerated, the Board does not minimize the difficulties associated with carrying out the research program that it recommends. Nonetheless, the Board restates its view that the key subset of issues associated with waste degradation and radionuclide transport deserves further attention because of the potentially significant effect that these phenomena might have on developing realistic estimates of repository performance.

Realistic Performance Assessments

Waste degradation and radionuclide transport is only one area where the Board believes that OCRWM's estimates of repository performance are unrealistic. In the past, the Board has called OCRWM's attention to the importance of eliminating, to the greatest extent possible, the use of "bounding assumptions," as opposed to realistic distributions of important parameters. Over the last two years, the Board has followed the development of the Project's performance-margin analyses, and it reaffirms its belief in the potential value of such analyses.

Bomb-Pulse Chlorine-36 at the Horizon of the Proposed Repository

Since mid-1996, the Board has followed closely Project investigations to determine whether elevated levels of bomb-pulse chlorine-36 are present at the horizon of the proposed repository. The presence of the isotope in undisturbed rocks at depth would provide incontrovertible evidence that at least some of the water that falls on Yucca Mountain moves rapidly through the unsaturated zone above the proposed repository.

Over the last seven years, the Board has urged OCRWM to resolve the apparent disagreement about this issue between Los Alamos National Laboratory, which believed that it found evidence suggesting the isotope's presence, and Lawrence Livermore National

Laboratory and the USGS, both of which failed to find any evidence of elevated bomb-pulse chlorine-36 levels. The Project has told the Board that it has abandoned efforts to reconcile the disparate findings. However, the Board still believes that the possible existence of bomb-pulse chlorine-36 at depth in Yucca Mountain remains an outstanding issue whose resolution could greatly enhance confidence in understanding fluid flow within Yucca Mountain.

The Crosscutting Issue of Thermal Management

How OCRWM plans to establish the temperature regime under which the proposed repository will operate strongly affects the acceptance of waste at generation sites as well as surface and subsurface operations at the facility. Thermal management also strongly influences projections of a repository's postclosure performance because the corrosion, near-field, and hydrologic models used in the TSPA all are temperature dependent.

Over the last two years, the Board's interactions with OCRWM on the thermal management issue have been productive. The Project is developing an integrated thermal management strategy using the TSM and waste package loading models to evaluate waste acceptance as well as surface and subsurface operations, including emplacement. It is considering different scenarios of assembly age, burnup, and throughput rates using actual assembly power decays rather than, as it has done in the past, a single decay rate based on a theoretical waste stream. The Board is encouraged by the progress that OCRWM recently has made in addressing its concerns related to this critical crosscutting issue.

Board Activities

The U.S. Nuclear Waste Technical Review Board (Board) was established by Congress in the Nuclear Waste Policy Amendments Act (NWPAA) (U.S. Congress 1987). The Act requires the Board to evaluate the technical and scientific validity of the work undertaken by the U.S. Department of Energy (DOE) under the Nuclear Waste Policy Act of 1982, as amended. Those laws require DOE to develop systems for disposing of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) produced by the nation's commercial nuclear power stations, nuclear defense complex, and research reactors. Currently, DOE, through its Office of Civilian Radioactive Waste Management (OCRWM), is working on a system that would consist of a geologic repository located at Yucca Mountain in Nevada, together with waste acceptance and transportation systems for bringing the waste to Yucca Mountain. The results of the Board's evaluation, along with its recommendations, must be reported at least twice yearly to Congress and the Secretary of Energy. This document is the first such report for 2008.

The Board's mandate to review the DOE's waste disposal project is broad. Between March 1, 2006, and December 31, 2007, the period covered by this report, the Board focused its evaluation on five critical technical issues dealing with preclosure operations of the waste management system and on six critical technical issues dealing with postclosure performance of the proposed Yucca Mountain repository. The Board also explored in depth the crosscutting issue of thermal management.

The Yucca Mountain Project made progress on achieving several important milestones, realized others, and established new ones. The Board considers all of these achievements significant accomplishments.

The Context of the Board's Review

On May 26, 2006, the Senate confirmed Edward Sproat, III, as Director of OCRWM. During the next 19 months, the Yucca Mountain Project made progress on achieving several important milestones, realized others, and established new ones. The Board considers all of these achievements significant accomplishments.

- In July 2006, Sproat testified before the Subcommittee on Energy and Air Quality of the Committee on Energy and Commerce in the U.S. House of Representatives. He stated that DOE would submit to the U.S. Nuclear Regulatory Commission (NRC)

no later than June 30, 2008, a License Application (LA) for constructing a repository at Yucca Mountain.[1] He noted that the "best achievable" schedule for beginning to receive waste would be 2017 (Sproat 2006).

- Building on an initiative that was launched in 2005, DOE made a series of decisions between July and October 2006 that significantly altered the design of the proposed repository's surface facilities. DOE's Energy Systems Acquisition Advisory Board authorized planning for construction of four structures: Initial Handling Facility (IHF), Receipt Facility (RF), Canister Receipt and Closure Facility (CRCF), and Wet Handling Facility (WHF). This design change reflects the Project's decision that most commercial SNF and all HLW should be sent to the proposed repository in standardized sealed transportation-aging-disposal (TAD) canisters that would not require repetitive handling of commercial SNF assemblies before their disposal (DOE 2006b). Earlier plans called for shipping SNF in various types of canisters to the proposed repository where, in preparing the material for disposal, workers would handle each of the bare SNF assemblies as many as four times in order to blend and package the fuel for disposal. DOE began developing a performance specification so that the materials used to fabricate the TAD canisters and to ensure that the projected performance of the canisters conformed to the assumptions of DOE's Total System Performance Assessment (TSPA).
- In October 2006, OCRWM completed the transition to Sandia National Laboratories (SNL) of the responsibility for managing and integrating all the Project's scientific activities related to postclosure performance of the proposed repository.
- In June 2007, OCRWM finalized the performance specification for the TAD system, which includes, among other things, a canister, a transportation overpack, a transfer cask, a storage overpack, and an aging overpack (DOE Office of Public Affairs 2007). OCRWM then initiated the procurement for the development of complete TAD system designs and safety analysis reports (SAR) for NRC certification under 10 CFR 71 and 10 CFR 72. Four proposals were received and are being evaluated.
- In October 2007, DOE published two draft environmental impact statements (EIS) to support decisions related to the construction of a rail line and the operation of a railroad within Nevada to transport SNF and HLW to Yucca Mountain (DOE 2007a, b). The first document evaluated the environmental impacts along one new corridor, the Mina route south of the town of Silver Springs. Further, updated information on the impacts along three other corridors–Carlin, Jean, and Valley Modified–which had been analyzed previously was evaluated to determine whether those corridors warranted additional detailed study. (Impacts along a fourth corridor, originating in the city of Caliente, had been evaluated extensively in 2002.)

  The second document evaluated the environmetal impacts of constructing a rail line and operating a railroad along specific track alignments. Impacts along one set of

[1] DOE submitted the LA to NRC on June 3, 2008.

alternative alignments within the Mina corridor were evaluated, as were the impacts along another set of alternative alignments within the Caliente corridor.[2]

- In October 2007, DOE also released a draft Supplemental Environmental Impact Statement (SEIS) for the proposed repository at Yucca Mountain (DOE 2007c). The SEIS was prepared to reflect changes in the Project that have taken place since 2002. These changes include, among other things, the design of the surface facilities, the decision to use TAD canisters, and the choice of the "mostly rail" mode for transporting SNF and HLW. Further, additional information and updated analytical tools permitted refined analyses of transportation impacts, preclosure operational impacts, and estimates of postclosure repository performance.

Board Review of OCRWM's Technical and Scientific Investigations

Overview

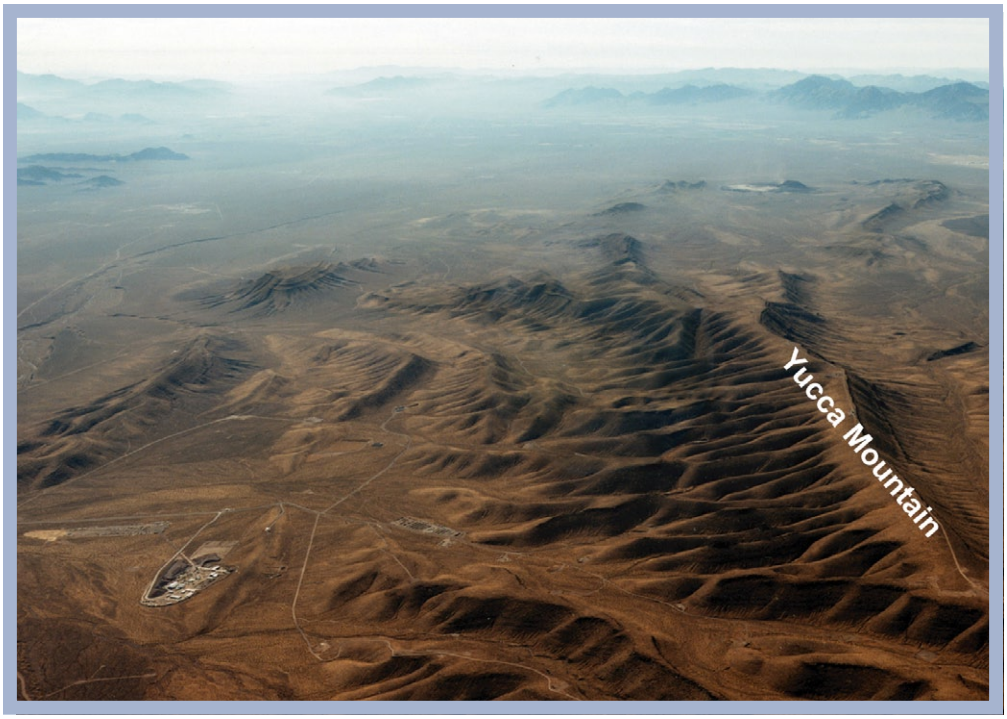
Throughout the period covered by this report, two fundamental questions guided the Board's activities.

- Are the scientific and technical bases for OCRWM's assessments of the postclosure performance of the repository valid and transparent?
- Has OCRWM established a safety case that integrates the total waste management system, from waste acceptance at the generator sites, to preclosure operations at and below the surface of the repository site, to performance demonstration and confirmation, and, finally, to the closure of the repository?

To obtain answers to these questions, the Board needed to interact with the Project in a concerted manner that permitted in-depth technical exploration of the issues. Many of those interactions took place in public meetings and workshops. Transcripts of those meetings and workshops and copies of the presentations that were made are available on the Board's web site: www.nwtrb.gov.

In addition, small contingents of Board members and staff held seven fact-finding meetings with OCRWM and its contractors between March 2006 and December 2007. Project scientists and engineers presented ongoing scientific investigations and analyses, many of which contained preliminary results in draft form, which the Board is entitled to receive under the NWPAA. These fact-finding meetings were productive and enabled the Board to engage in the detailed and lengthy technical discussions that are necessary for understanding many of the fundamental methods of analysis used by the Project. In addition, several Board members and staff held separate talks with representatives of railroads, trucking companies, cask manufacturers, transportation logistics providers, and nuclear utilities. The purpose of these sessions was to gather first-hand information from key stakehold-

[2] Because the Walker River Paiute Tribal Council decided in April 2007 to renew past objections to the transportation of HLW and SNF through its reservation, the Mina route was eliminated from consideration. Although DOE acknowledged that the Mina route would have been, on balance, environmentally preferable and cost $500 million less, DOE proposed to construct a rail line and to operate a railroad along one specific rail alignment within the Caliente corridor.



Source: DOE

Figure 1. Yucca Mountain

ers who would be involved in designing and operating the waste-management system. All of these meetings were undertaken to improve the technical substance and relevance of the Board's public meetings. To the extent possible, major conclusions reached as a result of these interactions will be discussed in this report.

The Proposed Repository System

Yucca Mountain is a north-south trending ridge, rising approximately 300 meters (1300 feet) above the adjacent valleys in Nye County, Nevada. It is approximately 160 kilometers (100 miles) northwest of Las Vegas. The site is located on land controlled by three U.S. Government agencies: the Department of Defense, the Department of the Interior, and DOE. **Figure 1** is a photograph of Yucca Mountain, taken looking south.

Nuclear waste in its variety of forms must be moved to Yucca Mountain from more than 100 sites where it is currently stored. DOE has determined that most of the material should be moved by rail, although some waste may have to be moved by truck or barge relatively short distances from where it is stored to a rail head. The proposed repository site, however, is not served by a rail line. As noted above, the Project has drafted two EIS's to support its plans for developing a new rail line and operating a railroad to move the HLW and SNF from a rail junction, likely to be in Caliente. Based on estimates in the EIS's, a new rail line constructed on the Caliente corridor would be approximately 500 kilometers (330 miles) long and would require establishing a right-of-way involving 170 square kilometers (41,000 acres). Including the construction of support facilities and the purchase of rolling stock, creating the capacity to move waste to Yucca Mountain would cost in 2005 constant dollars approximately $2.7 billion.

The surface part of the repository system is a large complex containing several buildings for processing the HLW and SNF as well as concrete pads for aging some of that material until its disposition. **Figure 2** shows the layout for the proposed surface facilities. According to Project plans, waste will arrive at Yucca Mountain in a variety of forms—commercial SNF from nuclear power stations that is either in TAD canisters or in dual-purpose casks (DPC); uncanistered commercial fuel assemblies; canistered HLW produced at DOE's defense facilities or at the West Valley Plant; canistered SNF from the Navy's nuclear warships; and canistered DOE SNF.

Once the waste is received, it will be sent to one or more of four buildings for processing. HLW and Navy SNF will be placed in waste packages in the IHF and disposed of immedi-

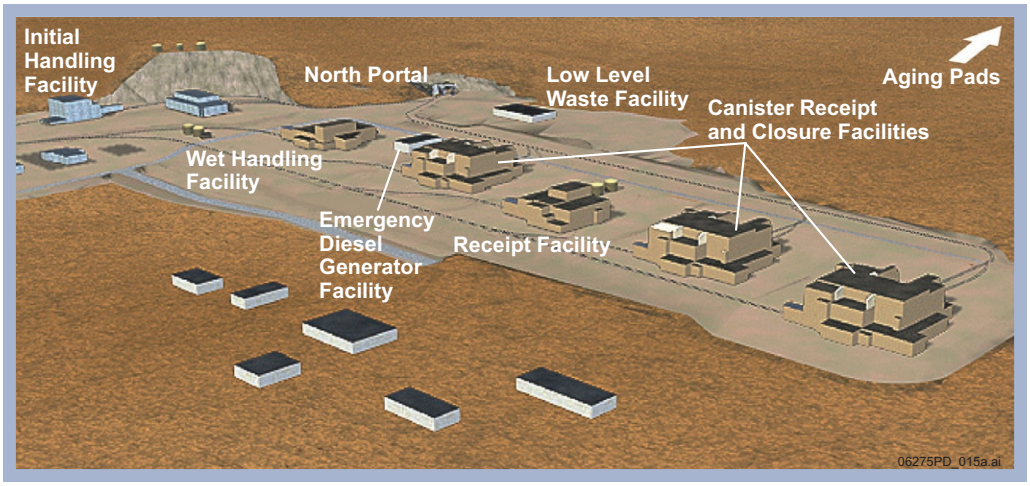


Figure 2. Surface Facility Layout

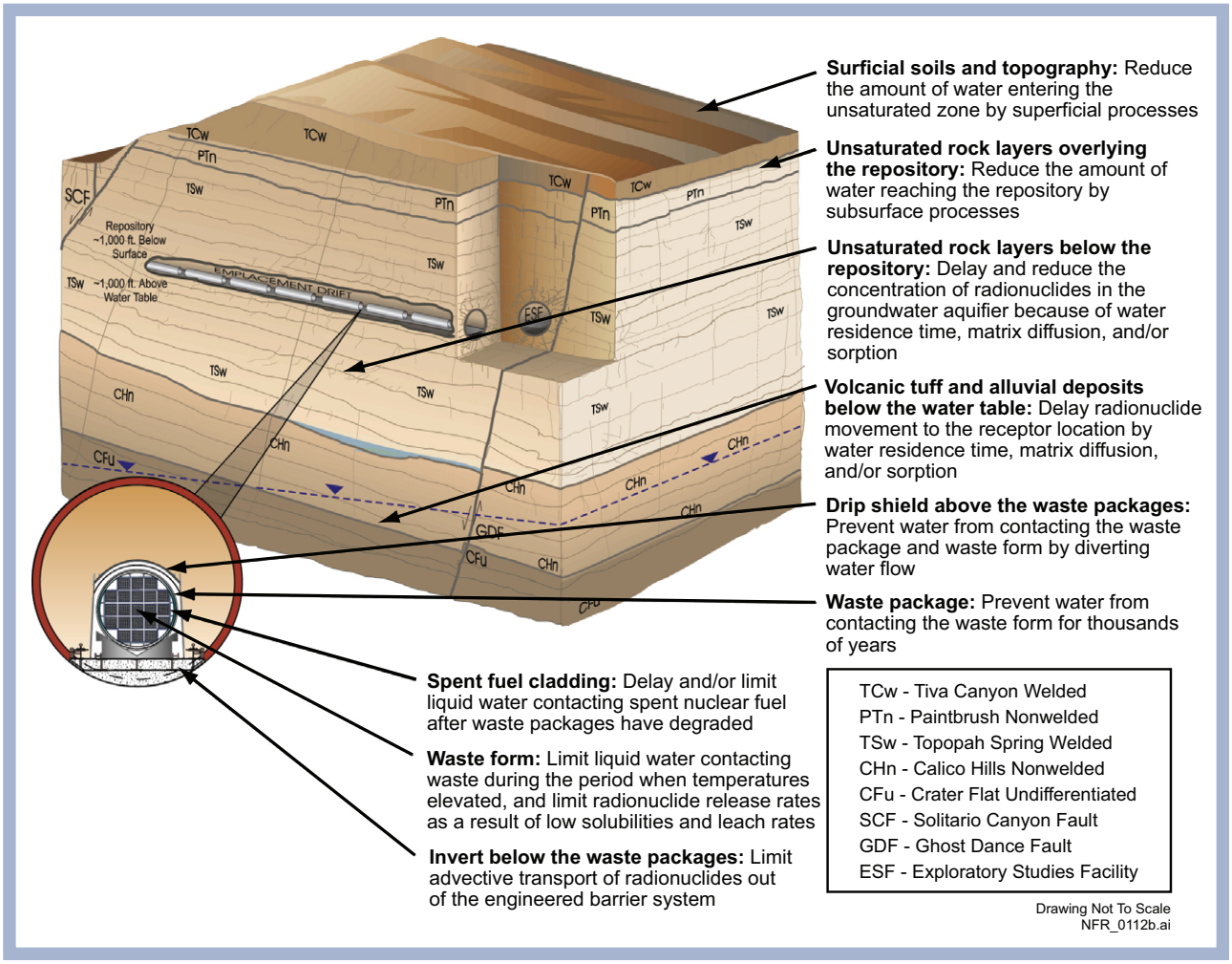
Source: DOE

ately. DOE SNF will be placed in waste packages in the CRCF and also will be disposed of immediately. Commercial SNF in TAD canisters can be processed either at the RF or at the CRCF. Commercial SNF in DPC's can be handled at the RF or at the WHF. Uncanistered commercial fuel assemblies can be accommodated only in the WHF, where it will be put in canisters. The now-canistered commercial spent fuel will be sent to the CRCF, where the canisters will be placed in the waste packages, which then will be sealed. The waste packages will then be disposed of. Commercial SNF, whose thermal power is too high for the waste to be disposed of immediately, will be placed on aging pads until its thermal power has decreased to a level acceptable for disposal. After the commercial SNF's thermal output has dropped sufficiently, it will be returned either directly or, in the case of SNF in DPC's, indirectly through the WHF to the CRCF. There, it will be prepared for final disposal.

The subsurface part of the repository system consists of both natural features and engineered elements. They are expected to work together to limit the amount of water contacting the waste and to retard or contain any material released. The surficial soil and topography and the unsaturated volcanic tuff above the repository drifts (tunnels) limit the amount of water that percolates downward. The amount of water that enters the drifts is a fraction of the water that reaches the horizon where the proposed repository would be located.

The SNF and HLW are inside robust waste packages whose outer shell is composed of a corrosion-resistant nickel-based metal called Alloy 22. Covering the waste packages are overlapping titanium drip-shield segments, which, while they are intact, can divert water from coming into direct contact with the packages. Only after the waste packages corrode and the waste form degrades will the radionuclides in the SNF and HLW be exposed to liquid water. It is possible that their migration immediately outside the package may be physically and chemically retarded. Even if it is not, the radionuclides must travel outside the drifts through another thick layer of unsaturated rock before reaching the formation that includes the water table. Once in this saturated zone, the radionuclides may be transported to the accessible environment and taken up mostly by people, animals, and plants living in the area downgradient of the site. **Figure 3** on the next page is a schematic that summarizes how the subsurface features and elements are expected to isolate waste.

Standards and regulations promulgated by the U.S. Environmental Protection Agency (EPA) and NRC regulations require that DOE calculate how large a dose the "reasonably maximally exposed individual" who resides about 18 kilometers (11 miles) south of Yucca



Source: DOE

Figure 3. Subsurface Features at Yucca Mountain

Mountain will receive (40 CFR 197 and 10 CFR 63).[3] To do so, DOE must construct complex computer models of the proposed repository's postclosure behavior and exercise them in a TSPA. In addition, the standards and regulations require that DOE evaluate the operational safety risks to the public and workers in a Preclosure Safety Analysis (PCSA).

Preclosure Operations of the Waste Management System

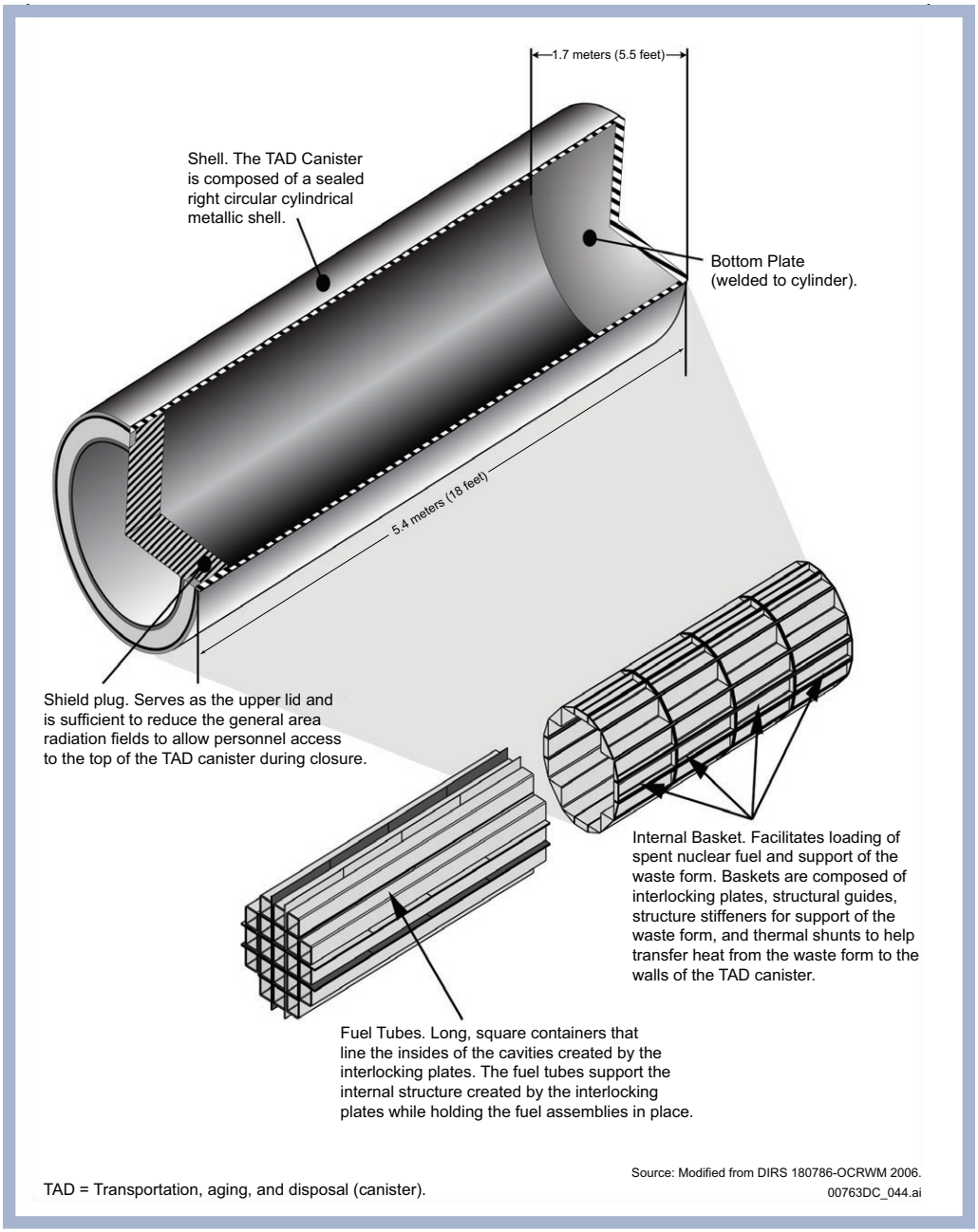
Transportation-Aging-Disposal Canister Concept

The TAD canister system could reduce the number of times individual assemblies are handled because the canister and its contents would be handled in a single action.

In 2005, DOE made a provisional decision to adopt the TAD canister concept. The following year, that decision was confirmed. **Figure 4** is a conceptual design of what a TAD canister might look like.

From the time that the TAD canister concept was first proposed, the Board held that it was promising (Garrick 2005b, c and NWTRB 2006a). "The TAD canister system could reduce the number of times individual assemblies are handled because the canister and its contents would be handled in a single action. This could improve facility throughput at Yucca Mountain and reduce the potential for accidents during handling operations.

[3] The U.S. Environmental Protection Agency is considering comments on its proposed environmental standards. Two key issues are what the permissible dose should be and the time period over which that dose cannot be exceeded. (For the proposed standard, see EPA 2005.)



Source: DOE

Figure 4. Conceptual Design of the TAD

The TAD canister system also has the potential to simplify the design and reduce the cost of repository surface facilities." (Garrick 2006a). Since then, the Board's views about the TAD canister concept, although tempered somewhat, have not changed fundamentally: The Board looks favorably on the technology but realizes that OCRWM still must address some important implementation issues. Of foremost importance to the Board are (1) the implications of the TAD canister concept for preclosure and postclosure thermal management at the potential repository; (2) the logistics of transporting TAD canisters to Yucca Mountain; and (3) how DOE will manage commercial SNF that is not packaged in a TAD canister.

At the Board's May 9, 2006, meeting in McLean, Virginia (NWTRB 2006b), an OCRWM official described the approach that will be used to develop and implement the TAD canister concept (Kouts 2006). From OCRWM's perspective, the concept offers important

advantages: The TAD canisters would standardize fuel handling, utilize utility fuel-handling experience, simplify operations at the repository, reduce low-level-waste production and worker radiation exposure, and lower the cost of building surface facilities at the proposed repository site. The private sector would be asked to provide detailed designs that would meet a suite of performance specifications, allowing the TAD canister system to satisfy NRC regulations for storage (10 CFR 72), transportation (10 CFR 71), and disposal (10 CFR 63). DOE would procure TAD canister system transportation overpacks and provide TAD canisters for acceptance of SNF directly from utility pools. Further, DOE has announced that it might offer economic incentives for encouraging utilities to purchase TAD canisters. In such cases, DOE also would provide storage/transportation overpacks to move the loaded TAD canisters to the proposed repository. In a complementary presentation, representatives from two nuclear industry trade associations noted that their members are committed to cooperating with DOE to bring the TAD canister concept to fruition (McCullum and Blee 2006).

The following year, at its January 24, 2007, and its September 19, 2007, meetings, both held in Las Vegas (NWTRB 2007 a, d), the Board received updates on the development process for the TAD canister system (Kouts 2007a, b). By the time the second meeting took place, a final performance specification had been issued, delineating the requirements that DOE will rely on in its LA. Subsequently, four cask vendors completed TAD-canister proof-of-concept designs, and DOE completed reviewing those designs. DOE initiated a procurement for developing complete TAD canister system designs and Safety Analysis Reports for NRC certification for storage and transportation. Four proposals were received. They are still being evaluated. The same two representatives of nuclear industry trade associations observed that the dialogue between their members and DOE had been positive and that agreements had been reached on a number of issues. The two representatives, however, cautioned that much work still needs to be done and that successful implementation of the TAD canister concept is by no means assured (McCullum and Blee 2007).

The Board commented on these developments in a series of letters to DOE.[4] In a June 14, 2006, letter (Garrick 2006a), the Board agreed that many of the advantages that OCRWM attached to the TAD canister concept might be realized. But the Board also noted that it had become apparent "that hurdles must be overcome for the potential advantages of a canister-based system to be realized. Particularly important is the timing of the availability of TAD canisters for storage at utility sites … If TADs are not available for use at utilities for at least 5-6 years, the quantity of spent fuel in dry storage [in containers other than TADs] at reactor sites will be significant."

. . . hurdles must be overcome for the potential advantages of a canister-based system to be realized.

In a January 16, 2008, letter (Garrick 2008), the Board again questioned OCRWM's projection that 90 percent of commercial SNF would be placed in TAD canisters. For that reason, the Board again recommended that "DOE carry out comprehensive analyses to understand better the implications of not achieving the 90 percent TAD canister utilization rate. Furthermore, the Board continues to encourage DOE to study actively all possible options for dealing with spent nuclear fuel in dual purpose canisters—including direct disposal." The Project has not yet provided the Board with any analysis that supports the 90 percent assumption.

[4] See also the Board's findings and recommendations in an earlier report (NWTRB 2006c).

Surface Facility Operations

During the period covered by this report, OCRWM devoted considerable energy to implementing the initiative, launched in 2005 and approved in 2006, to redesign the surface facilities at the proposed repository. Project representatives discussed the status of those efforts at three Board meetings. At the May 9, 2006, meeting, an OCRWM manager provided an overview of the process by which the DOE would switch its design basis to the new surface facilities (Harrington 2006 and NWTRB 2006b). He also explained the potential effects on the PSCA. At the January 24, 2007, meeting in Las Vegas, the Project manager reported that the basic facility layouts and material flows had been completed, that the "lumped mass structural model" for the CRCF had been finalized, and that the structural and system designs were in process (Harrington 2007 and NWTRB 2007a). He also described in very broad terms what the four major surface facilities might look like.

In an April 19, 2007, letter to OCRWM, the Board requested additional information about the design of the surface facilities. The Board also encouraged the Project "to evaluate surface-facility designs and operational concepts for opportunities to reduce the number of times waste is handled." The Board also urged OCRWM "to evaluate the safety, operational, and economic issues related to opening, unloading, and disposing of empty DPC's in comparison to possible direct disposal of DPCs in Yucca Mountain" (Garrick 2007b). In response, OCRWM observed in a November 6, 2007, letter that it had eliminated at least three and as many as six lifts. OCRWM, however, told the Board that the direct disposal of DPC's is not included in the LA that is being prepared, nor are there plans for preparing amendments to the LA, which might be submitted at a later date. OCRWM believes that there are important questions related to criticality that must be resolved before DPC's can be disposed of directly. Until then, OCRWM plans to cut open DPC's in the WHF and transfer the fuel assemblies to TAD canisters (Sproat 2007b). The Board notes that the disposal of commercial SNF in TAD canisters will require that the NRC grant the same burnup credit as for the direct disposal of DPC's. Additional work, however, will be needed to analyze whether the criticality controls within the DPC will eliminate potential events throughout the entire compliance period, which may last as much as one million years. The Board encourages the Project to undertake those additional analyses expeditiously.

A Project representative presented an update on facility design at the Board's September 19, 2007, meeting (Slovic 2007 and NWTRB 2007d). Although the description of the facilities had matured somewhat, very little detailed information was provided about the designs. Among the specifics that the representative did discuss were preliminary estimates of throughput for the various surface facilities. In a January 16, 2008, letter to OCRWM, the Board held that the preliminary estimates of throughput appeared "overly optimistic" (Garrick 2008). The Board recommends that OCRWM more realistically represent throughput processes. The Board also recommends that the Project evaluate a number of measures that could improve throughput, including increasing the capacity of the WHF pool to allow parallel removal and transfer of fuel contained in DPC's and increasing the number of welding stations in the WHF and the CRCF to eliminate potential choke points. Further, for assessing operational risk and the viability of the waste management system, the Board recommended that OCRWM develop a "series of realistic and detailed throughput analyses that go beyond a deterministic, steady-state approach. Such analyses should consider potential off-normal operational scenarios and should specifically address the

The Board held that the preliminary estimates of throughput appeared "overly optimistic." The Board recommends that OCRWM more realistically represent throughput processes.

throughput achieved by individual surface facilities, the integrated surface facility complex, and the waste management system as a whole."

The subject of engineering prototyping arose at the Board's September 27, 2006, meeting in Armagosa Valley, Nevada (NWTRB 2006e). In a December 14, 2006, letter, the Board strongly encouraged OCRWM to develop a robust prototyping program for what will be a first-of-a-kind undertaking. "Examples of specific elements that could benefit from engineering prototyping include waste package fabrication, loading, sealing, and emplacement; robotics; and drip-shield emplacement" (Garrick 2006b). In an August 13, 2007, letter to the Board (Sproat 2007a), OCRWM agreed with the Board's recommendations about prototyping. Waste package closure equipment, the waste package and pallet, and the drip shield are among the items for which prototypes are planned. Notwithstanding this response, the Board understands that the prototyping program has been deferred until at least fiscal year 2009. The Board restates its view that this should be one of the Project's most important priorities.

Finally, at a January 24, 2007, meeting in Las Vegas, the Board heard about work being undertaken by the Project on seismic ground motion (Dyer 2007 and NWTRB 2007a). The objectives of those investigations include the development of a seismic-hazard curve for the surface facility area to be used in the PSCA, based in part on updated preclosure ground-motion estimates, which benefited from recently collected geotechnical data. For several years, the Board has encouraged OCRWM to develop more-realistic estimates of ground motion for the preclosure period. (See, for example, NWTRB 2003a and Corradini 2003b.)

In an April 19, 2007, letter (Garrick 2007b), the Board observed that OCRWM's use of overly conservative estimates has driven the Project to design surface facilities whose walls are made of four-foot-thick steel-reinforced concrete. The Board reiterated its view that the Project still needed to develop more-realistic seismic ground-motion estimates. In a November 6, 2007, letter to the Board (Sproat 2007b), OCRWM explained that it was refining its seismic analyses. "In updating these ground motions, an alternate approach to incorporating site response has been implemented that results directly in a site-specific seismic hazard curve. In addition, reasonable limits to extreme (very low probability) ground motions at YM are directly incorporated." The Board is pleased with the direction that OCRWM is taking on this issue.

Preclosure Safety Analysis

OCRWM is preparing a PCSA, which must be carried out as part of the LA (10 CFR 63.112). As of the end of 2007, that effort had not been completed.

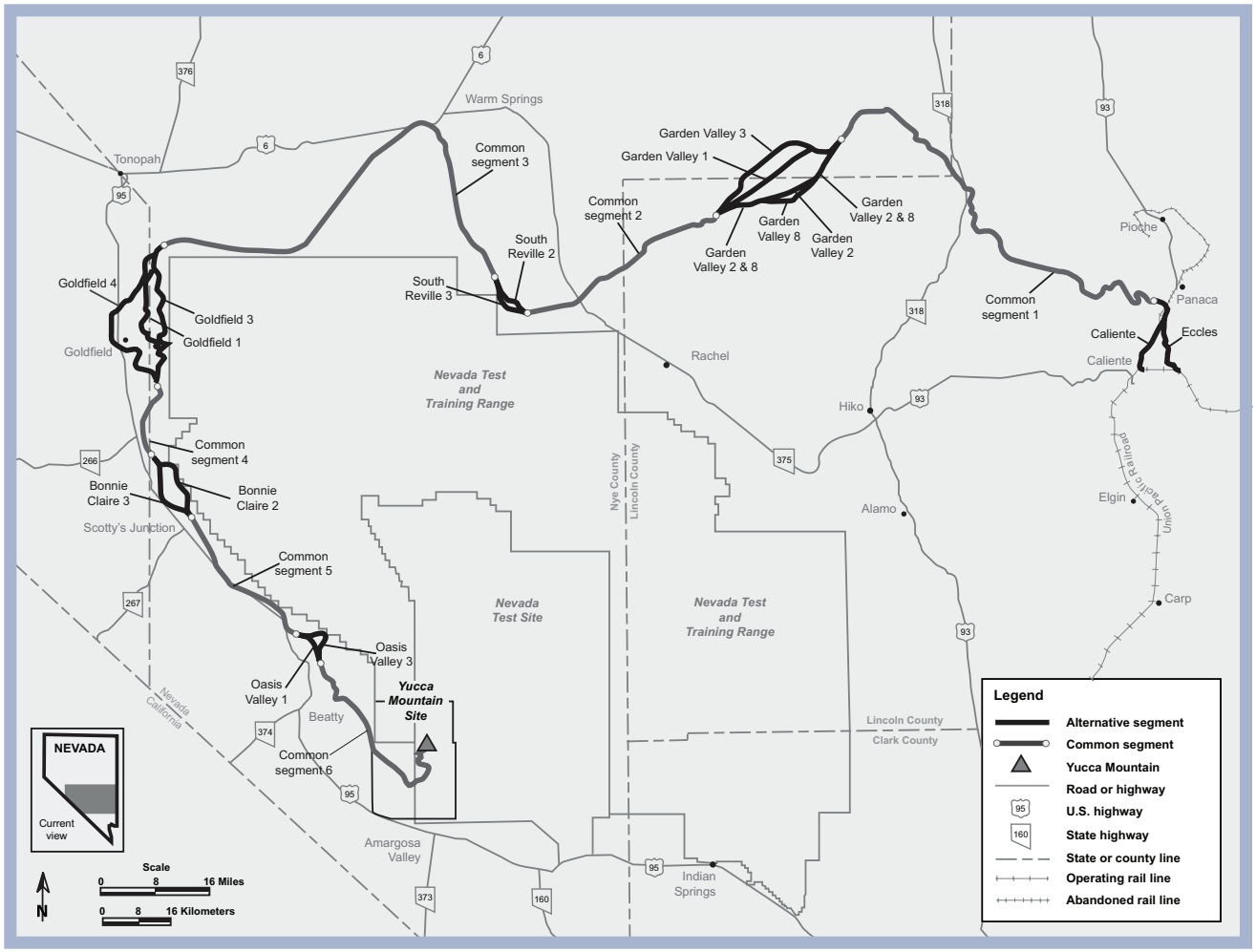
At the Board's September 19, 2007, meeting in Las Vegas (NWTRB 2007d), a Project analyst described the underlying philosophy and approach being taken (Frank 2007). In its January 16, 2008, letter to OCRWM (Garrick 2008), the Board expressed its concern that "the approach outlined for the development of the PCSA is a combination of deterministic and risk-informed, probabilistic methodologies. How [OCRWM] intends to address the uncertainties associated with the aggregation of risk is not clear to the Board. The Board would like [OCRWM] to explain in greater detail how the PCSA will address the remaining design uncertainties." As of the publication of this report, OCRWM has not provided such an explanation to the Board.

Transportation

For the last two years, the Project has cited budget constraints as a limiting factor in developing a transportation system to move HLW and SNF from generator sites to the proposed repository at Yucca Mountain. In addition to sponsoring cooperative agreements with state regional groups, such as the Council of Governments, and interacting with stakeholders at twice-a-year meetings of the Transportation External Coordination Working Group, OCRWM published two draft EIS's evaluating two rail corridors within Nevada and assessing the effects of choosing a specific rail alignment within two of them. The Project, however, was unable to move forward with any of its major procurements, especially those associated with constructing and operating a rail line within Nevada.

The Board remains concerned that the Project does not fully appreciate the ramifications of potential delays in the construction of a rail line to Yucca Mountain or the possibility that a rail line may never be built. When DOE declared that the TAD canister would be the centerpiece of its waste management strategy, this implicitly made the Project dependent on the existence of a Yucca Mountain rail line.[5] **Figure 5** illustrates the proposed rail route from Caliente, Nevada to Yucca Mountain.

Figure 5. Proposed Rail Route from Caliente, Nevada, to Yucca Mountain



Source: DOE

[5] The size and the weight of the TAD canister preclude the use of the truck mode unless states, including Nevada, issue special permits, perhaps for each shipment.

Given that no such line exists today and that construction of such a line may encounter significant challenges, the absence of a workable alternative for such a vulnerability is not prudent. Therefore, the Board believes that OCRWM should immediately and aggressively pursue a contingency plan in which the truck mode (heavy-haul or off-road) is considered within Nevada. Such an approach might include a lighter-weight TAD-like canister that can be transported on a truck chassis or other means of packaging and moving waste via truck from generator sites to Yucca Mountain. Although the Project asserts that these contingencies are being considered, the Board has seen no evidence that OCRWM is devoting sufficient effort to this problem.

Waste Management System Integration

The Board conceives of a waste management system composed of four elements: waste acceptance, transportation, surface operations, and subsurface operations. It is imperative that the system be analyzed and evaluated as an integrated whole.

The Board conceives of a waste management system composed of four elements: waste acceptance, transportation, surface operations, and subsurface operations. It is imperative that the system be analyzed and evaluated as an integrated whole. Although the Project has made sporadic efforts over the last two years to do that, it as often has continued to conduct much of its planning and assessments in a disaggregated fashion. (See, for example, Garrick 2007b.)

One potentially important integrating methodology is OCRWM's Total System Model (TSM). The Board heard two presentations on the TSM, the first at its May 9, 2006, meeting in McLean, Virginia (NWTRB 2006b), the second at its January 24, 2007, meeting in Las Vegas (NWTRB 2007a). At both meetings, a Project manager noted that TSM is a "tool to analyze the linkages, interactions, and synergies between [sic] Program functions (waste acceptance, transportation, and repository.)" (Kouts 2006, Kouts 2007b). He provided an overview of TSM's structure, described many of the key variables included in the model, and discussed illustrative results that had been obtained. He reported that TSM continues to be used as designs are refined to do the following:

- Evaluate alternative system configurations and processing capabilities.
- Identify potential disconnects between various components of the waste management system.
- Assess ways to minimize the size of aging pads.
- Support repository postclosure thermal response.

In two letters to OCRWM, the Board strongly supported the use of TSM. In a June 14, 2006, communication, the Board observed that "it applauds DOE's development and use of TSM and encourages additional enhancements of its capabilities" (Garrick 2006a). In the same vein, the Board held in an April 19, 2007, letter that TSM "can play a valuable role in analyzing the operational interdependencies of the waste management system and the utility of the transportation, aging, and disposal (TAD) canister" (Garrick 2007b).

Nonetheless, the Board recommended areas where the TSM could be strengthened. For example, in its June 14, 2006, letter:

> Board recommends adding to TSM the capability to evaluate "upset" conditions, such as equipment breakdowns or closure of transportation routes, but only after the reference case is established. Moreover, implementation of TAD will have implications for the thermal man-

agement strategy that do not appear to have been considered fully. Consequently, the Board encourages adding to TSM the functionality to model DOE's thermal-management strategy. That could be accomplished by developing a constraint on waste package emplacement that ensures compliance with DOE's line-load thermal limit for the underground facility. For existing capabilities, as well as those that might be added in the future, realism will be important, if the results of TSM analyses are to be credible. The Board encourages DOE to scrutinize the TSM input assumptions and parameter values to ensure that they realistically represent the system being modeled (Garrick 2006a).

OCRWM stated in an August 13, 2007, letter to the Board (Sprout 2007a) that it "will continue the integrated system engineering and analyses approach to gain a greater understanding of the interrelationships between subsystem components—waste acceptance, transportation, and repository operations."

The Board believes, however, that this response to the Board's findings and recommendations regarding the use and enhancement of TSM does not adequately address its concerns. Although the Project has increased its reliance on the use of TSM to improve understanding of the performance of an integrated waste management system, this modeling framework has yet to be utilized in a manner that is fully representative of the design and operating considerations that OCRWM must address to ensure a compatible and functional preclosure repository operation. Of particular importance for achieving this objective are the following:

- The use of TSM as a comprehensive tool for representing and evaluating performance of the entire preclosure waste management system, including its components (waste acceptance, transportation, surface facility handling, subsurface operations) and component interactions.
- Sufficient quality assurance of the assumptions and modeling environment that constitute TSM and the manner in which the model is applied.
- The ability to represent stochastic scenarios, reflective of normal variations in processing times associated with various waste management system components, as well as upset conditions, such as those associated with construction delays, accidents, equipment failure, natural disasters, and intentional acts.

Addressing these considerations will increase confidence that the preclosure waste management system will function efficiently and effectively.

Postclosure Performance of the Proposed Repository System

Extensive field and laboratory studies as well as detailed analyses were undertaken by OCRWM to develop both qualitative and quantitative estimates of how a repository might perform hundreds of thousands of years into the future. The Project's efforts to develop those estimates have become increasingly sophisticated and evidence-based. The Board commends OCRWM for undertaking a broad suite of investigations, which often break new scientific and technical ground.

In evaluating the scientific and technical basis for the Project's estimates, the Board has identified six areas where improvements and enhancements still can be made. Although some additional work would be required to address Board concerns, the Board does not believe—with the possible exception of realistic waste degradation modeling—that this

The Project's efforts to develop those estimates have become increasingly sophisticated and evidence-based. The Board commends OCRWM for undertaking a broad suite of investigations, which often break new scientific and technical ground.

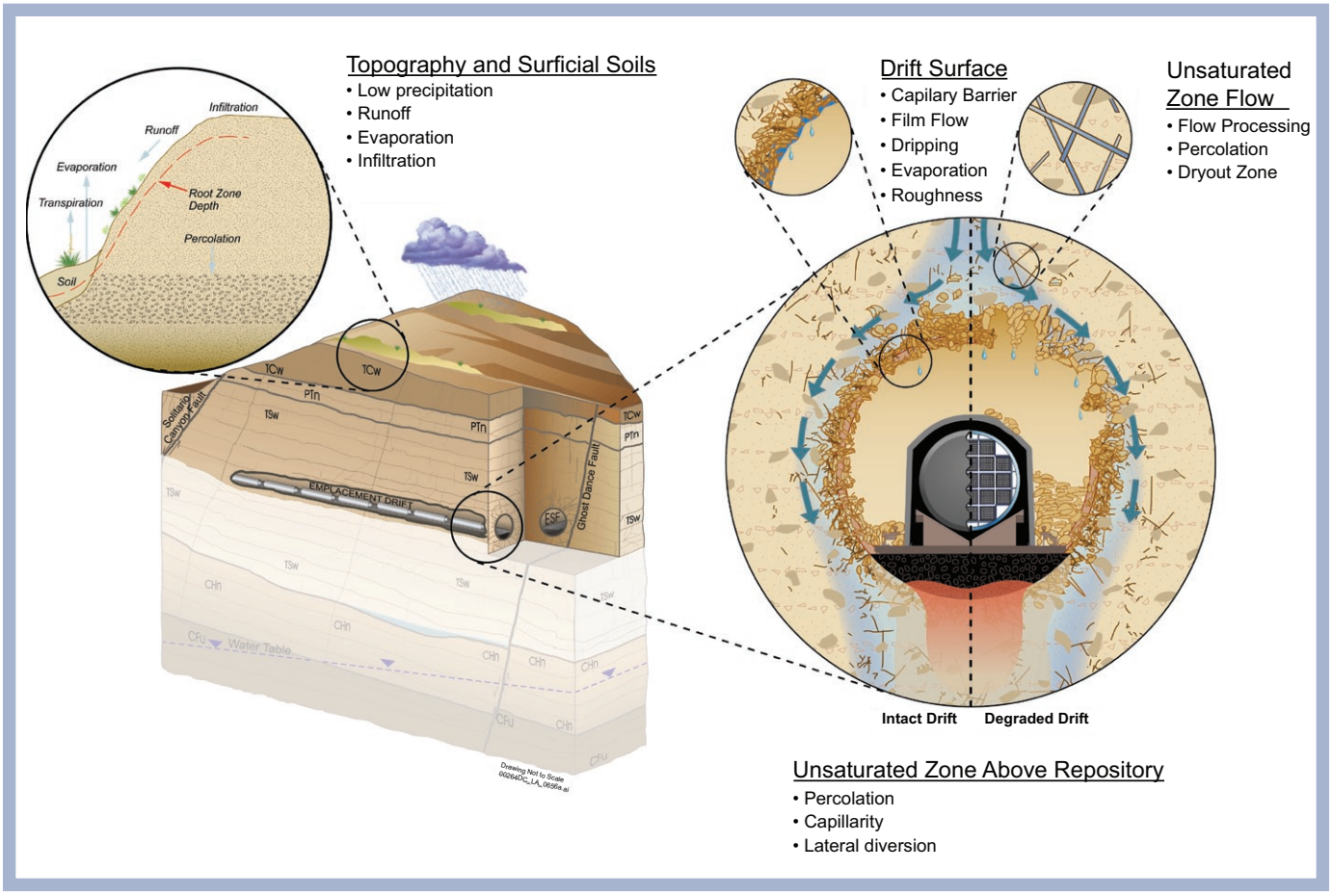
work would be especially difficult to carry out. In any event, completing this work could enhance the confidence that can be placed in the Project's performance estimates.

Capability of the Natural Barriers to Isolate and Contain Radionuclides

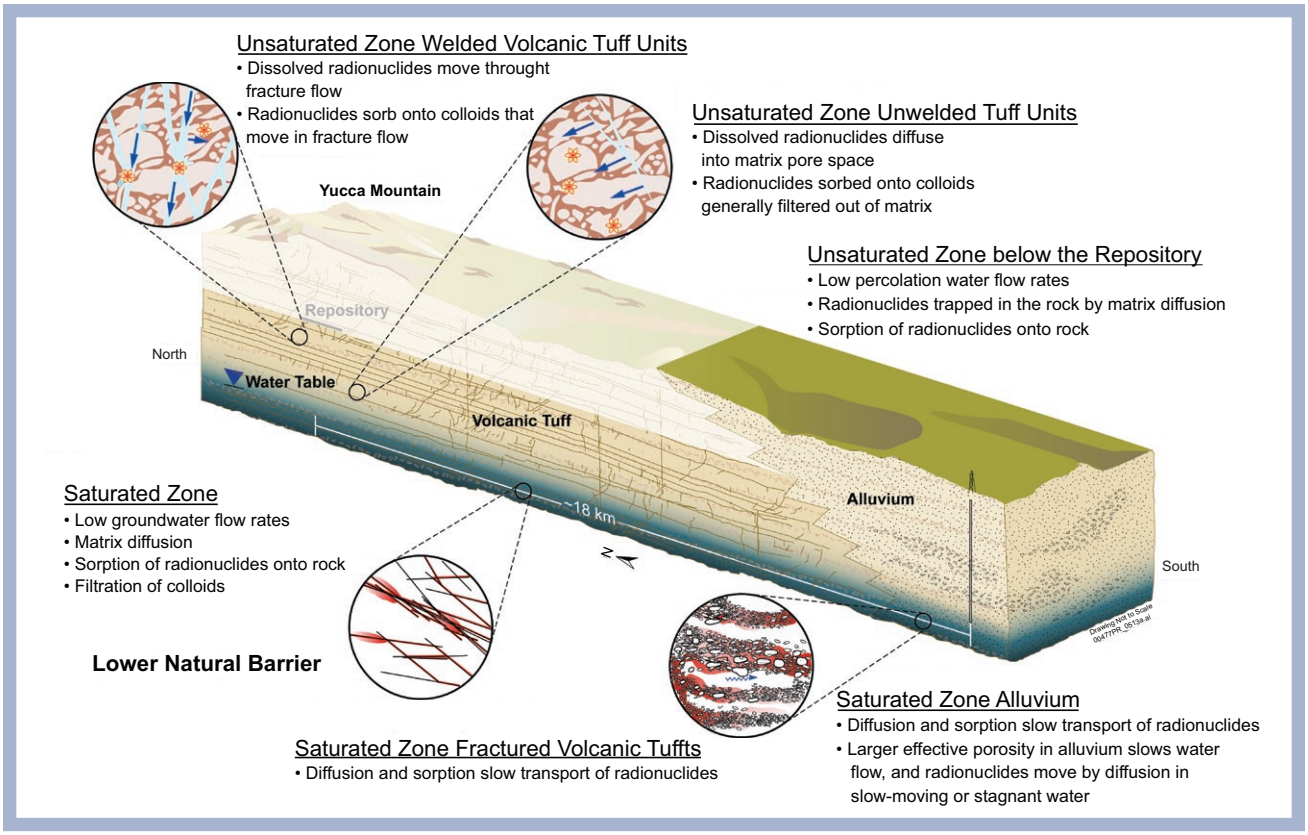
The potential natural barriers at Yucca Mountain may be grouped into two broad categories: the upper natural barrier and the lower natural barrier. The upper natural barrier is composed of the surficial soil and the unsaturated zone above the horizon where the proposed repository would be located. The lower natural barrier includes the unsaturated zone below the horizon of the proposed repository and the saturated zone. These natural barriers control the flow of water to the engineered elements of the repository system and subsequent radionuclide transport to the accessible environment, respectively. In addition, some rocks retard or otherwise slow transport of some radionuclides. However, rock heterogeneities, especially factures, zones of fracture concentration, and faults, can reduce the time required for radionuclides to reach the accessible environment. **Figure 6** and **Figure 7** depict these barriers.

During the period covered by this report, the Board reviewed certain aspects of OCRWM's work related to the upper and lower natural barriers. For example, at its May 15, 2007, meeting in Las Vegas (NWTRB 2007c), Project scientists gave talks on near-field chemistry (Brady 2007) and saturated-zone testing (Reimus 2007). Each of the presentations provided insights into OCRWM's technical and scientific activities.

Figure 6. Topography and Surface Soils



Source: DOE



Source: DOE

Figure 7. Saturated and Unsaturated Zones below the Repository.

The Board's most sustained effort was directed toward estimates of how much water infiltrates down from the surface to the horizon where the proposed repository would be located. The amount of water that infiltrates is an important variable in projecting long-term repository performance because water influences corrosion processes, affects the transport of any radionuclides that might be released from the waste package, and is the principal pathway through which the public, animals, and plants are exposed to possible releases from the repository.

OCRWM's Technical and Scientific Investigations Related to Infiltration

In March 2005, Secretary of Energy Samuel W. Bodman announced that e-mail had been discovered indicating that "certain employees of the U.S. Geological Survey (USGS) working on the Yucca Mountain Project may have falsified documentation of their work." The documentation in question related to computer modeling involving water infiltration (DOE Office of Public Affairs 2005). Testifying before the Committee on Government Reform of the House of Representatives the following month, Board Chairman B. John Garrick stated (Garrick 2005a):

> It would be inappropriate for the Board to draw any conclusions at this time about the significance [of the possible falsified documentation] for the technical work at Yucca Mountain… Answers to questions that might be raised…should await the completion of comprehensive investigations already underway at the Departments of Energy and Interior. The Board will follow the progress of those investigations, and when they are concluded, the Board will evaluate the significance of the results for the DOE's technical and scientific work. We will then report our findings to Congress and the Secretary of Energy.

In February 2006, OCRWM released a report detailing the results of its investigation (DOE 2006a). OCRWM maintained that the net infiltration ranges developed by the USGS were "consistent with groundwater recharge rates determined by other scientists studying other arid and semi-arid regions in the United States." Notwithstanding this conclusion, OCRWM said that it will "replace or supplement the infiltration modeling work, as needed, and will review or verify the supporting documentation…" (DOE Office of Public Affairs 2006; see also Runkle 2007).

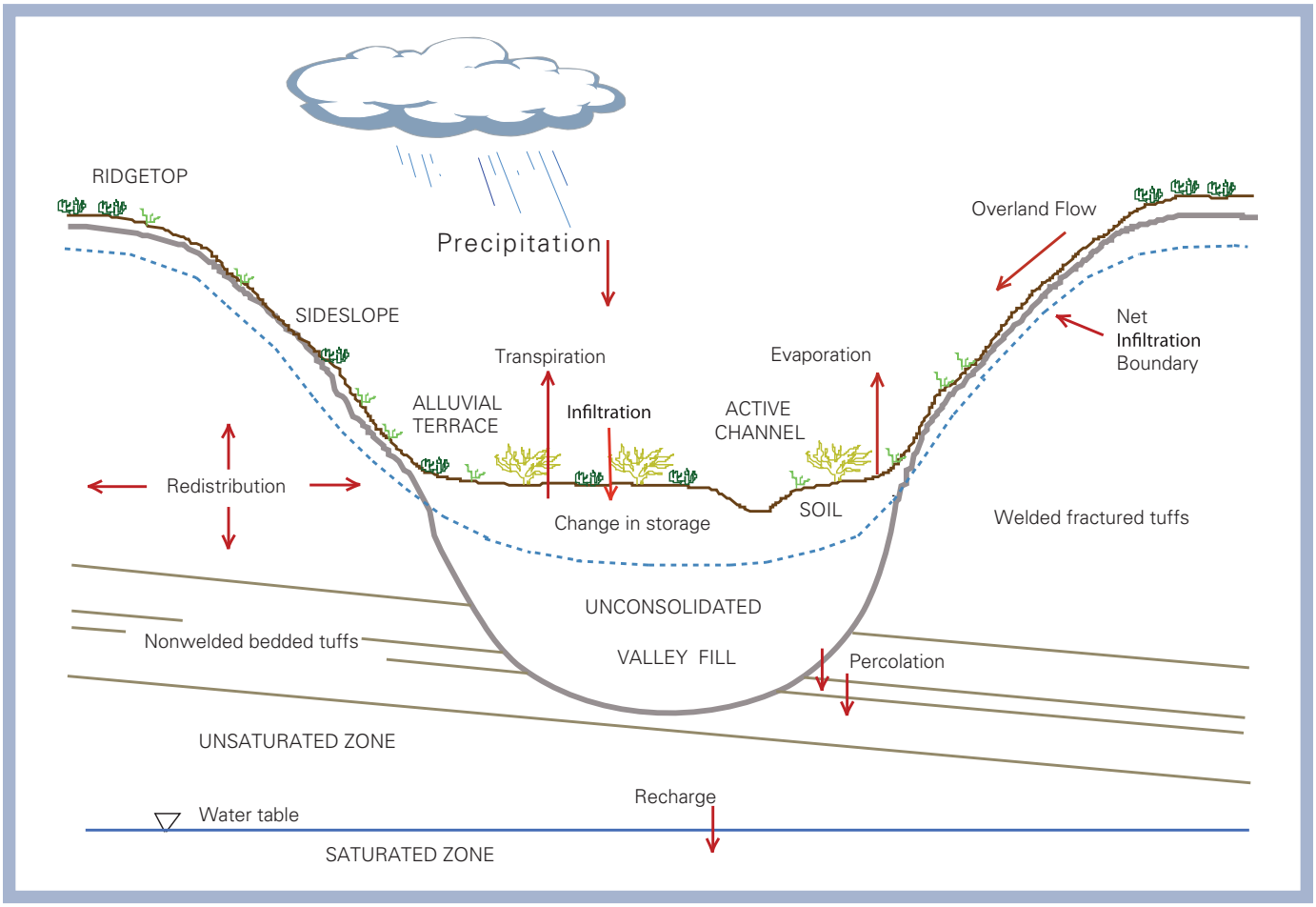
As part of its response to questions about USGS infiltration estimates, OCRWM undertook two parallel investigations. First, OCRWM commissioned an independent review by the Idaho National Laboratory (INL) of both the technical validity of USGS infiltration estimates and the compliance of those analyses with quality assurance (QA) protocols. That review has been completed. The primary findings of the INL study are that the USGS infiltration estimates have a sound technical basis and that deficiencies associated with the USGS analyses are confined primarily to inconsistencies with some QA protocols. Concurrently with the INL effort, DOE contracted with Sandia National Laboratories (SNL) to develop a new procedure for calculating infiltration at Yucca Mountain that would enable OCRWM to replace USGS infiltration estimates in all future assessments of repository performance, if necessary. The work by SNL also has been completed. Thus, there are two sets of infiltration estimates for Yucca Mountain: the USGS estimates and the SNL estimates.

The Board published its findings in a December 2007 report (NWTRB 2007e). The Board's evaluation focused solely on the technical aspects of actions undertaken by the USGS and DOE in response to concerns raised by the e-mail and on the potential effects of those actions on the technical basis for OCRWM's estimates of performance at Yucca Mountain. The Board evaluation consisted of technical review of the following: (1) the "old" USGS estimates of infiltration and the underlying technical bases of those estimates; (2) the "new" SNL estimates of infiltration and the underlying technical bases of those estimates; (3) the effects of the SNL estimates as used in performance assessment calculations; and (4) the value and credibility of existing data that could be used to support infiltration estimates.

The Board's evaluation concentrated on five factors most significant to estimates of infiltration at Yucca Mountain:

- *Precipitation:* the principal source of water for infiltration at Yucca Mountain.
- *Evapotranspiration:* the sum of water loss due to evaporation and water loss due to uptake by plants.
- *Soil depth:* the thickness of unconsolidated sediment lying above bedrock.
- *Soil hydraulic properties of hydraulic conductivity and porosity:* parameters that describe how readily water can flow through soil at Yucca Mountain and the water-storage capacity of the soil, respectively.
- *Rock hydraulic conductivity:* the capability of water to flow through rocks at Yucca Mountain.

Figure 8 illustrates the geologic environment that controls the infiltration of water into the unsaturated zone above the horizon where the proposed repository would be located.



Source: Flint (2007)

Figure 8. The Geologic Environment Controlling Infiltration.

In evaluating the technical basis supporting OCRWM's infiltration estimates, the Board engaged in various activities, including reviewing findings from investigations conducted by the Department of the Interior and DOE; reviewing DOE's technical assessments; and conducting field interviews with scientists and engineers at SNL, INL, and USGS. On March 14, 2007, the Board's Panel on Postclosure Performance held a one-day public meeting in Berkeley, California, on the scientific and technical bases of USGS and SNL estimates of infiltration (NWTRB 2007b). At that meeting, scientists from USGS, the Project, Los Alamos National Laboratory, SNL, and Lawrence Berkeley National Laboratory gave presentations on their findings and discussed the implications of these findings. For the present-day interglacial climate, the new SNL estimate of 14.3 mm/yr median annual infiltration is more than three times larger than the old USGS estimates of 3.6 mm/yr mean annual infiltration. For the monsoon climate state, new SNL estimates were about a factor of three greater than those developed by the USGS. For the glacial transition climate state, the SNL estimates were approximately two times greater than the USGS's results.

Board Findings and Recommendations Related to Infiltration

Calculating infiltration in a desert environment is a challenging technical and scientific undertaking. Infiltration is estimated using computer models in which factors such as rainfall, soil depth, water extraction from soil and rocks by plants and evaporation, and a host of other variables must be specified. Minor deficiencies in the USGS model were

identified by OCRWM and USGS reviewers, but no significant errors in USGS infiltration estimates were found. The Board found no significant errors in the computational approach used for infiltration estimates by either the USGS model or the SNL model.

. . . if all available relevant site-specific data at Yucca Mountain are used in both the USGS model and the SNL model, then repository performance estimates that are based on the infiltration estimates from either model should be essentially the same.

When the values of variables and the simulated natural processes are specified to be the same in the USGS and the SNL models, infiltration estimates from the two approaches are similar. The Board's opinion is that if all available relevant site-specific data at Yucca Mountain are used in both the USGS model and the SNL model, then repository performance estimates that are based on the infiltration estimates from either model should be essentially the same.

Information presented at the Board's March 14, 2007, panel meeting made clear that USGS estimates of infiltration are based on an extensive suite of site-specific data and are consistent with multiple independent lines of evidence. Furthermore, the Board's opinion is that the USGS program produced valuable results that are important for understanding the mountain hydrology and for building confidence in the estimated performance of the proposed repository.

In contrast, the SNL model does not include consideration of all available site-specific data that were used by USGS, such as soil depth, soil and rock hydraulic parameters, and the effects of evapotranspiration from shallow buried layers of bedrock. Consequently, SNL estimates of present-day infiltration at Yucca Mountain are approximately three times higher than the USGS estimates, and the SNL model results are less consistent with independent lines of evidence, including measurements of temperature and salt (chloride) concentrations at depth within Yucca Mountain. However, the SNL procedure has a more complete representation of uncertainties associated with relevant physical parameters—a methodological advantage over the USGS approach.

Infiltration estimates are used as input to estimates of potential long-term repository performance at Yucca Mountain in TSPA. To make the SNL estimates compatible with observed site-specific data supporting related models in TSPA, the Project uses a statistical process, called GLUE,[6] which preferentially considers the lower end of the range of SNL infiltration estimates. As used by the Project, the statistical modification of the infiltration estimates does not have a strong technical basis.

Although the effects on the regulatory process of QA infractions were not part of the Board's purview and therefore were not part of the Board's evaluation, the Board notes that compliance with QA procedures is an important part of the licensing process. However, even when scientific endeavors are not conducted in strict compliance with QA procedures, the fruits of those endeavors can have significant value. Conversely, strict observance of QA procedures is not by itself sufficient to guarantee sound technical and scientific analyses or data.

These findings led the Board to make the following recommendations (NWTRB 2007e).

- OCRWM should use all available site-specific data in its estimation of infiltration. Relevant USGS data found to have transparency or traceability QA discrepancies should be requalified and used in estimates of infiltration.

[6] As used by DOE, GLUE preferentially gives greater statistical weight to infiltration estimates that are more consistent with observed temperature and salt (chloride) measurements. See Beven and Binley (1992), SNL (2007), and Vogel et al. (in press).

- Because estimates of infiltration are necessarily imprecise, the Board recommends that OCRWM calibrate the infiltration model, using all relevant site-specific data.
- Because plant uptake of water from bedrock fractures is likely to occur at Yucca Mountain, the Board recommends that OCRWM include parameterization—including associated uncertainty—that represents evapotranspiration from shallow buried bedrock in its model.
- The Board does not endorse the use of the statistically modified SNL infiltration estimates in TSPA.

The Board's report on infiltration benefited from open and honest communication with involved scientists, all of whom demonstrated a strong personal commitment to developing a sound fundamental understanding of infiltration at Yucca Mountain.

Capability of the Engineered Barrier System to Isolate and Contain Radionuclides

The engineered barrier system (EBS) consists of man-made components designed to prevent the release of radionuclides. It includes the waste form,[7] waste package, drip shield, pallet, invert, and the drifts. Together, these elements of the EBS contain and isolate waste from the accessible environment. **Figure 9** on the next page presents a stylized drawing of the EBS.

OCRWM's Technical and Scientific Investigations Related to Deliquescence-Induced Localized Corrosion

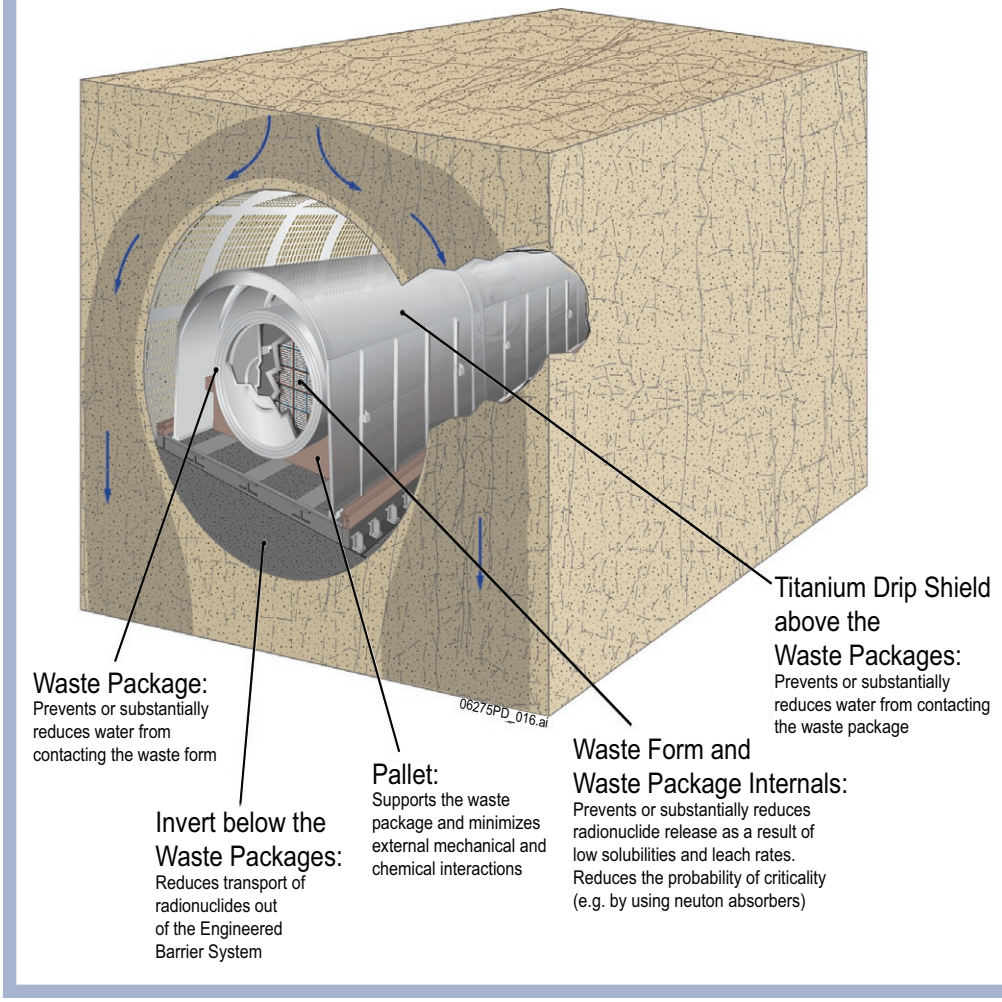
For the last few years, the Board has explored whether localized corrosion of the Alloy 22 waste package might occur at temperatures higher than approximately 140°C from the action of brines formed from deliquescent salts that could be present on waste package surfaces (Corradini 2003a, 2003c; NWTRB 2003b). After the meeting held in May 2004 (NWTRB 2004b), the Board concluded that deliquescence-induced localized corrosion due to calcium chloride brines during the higher-temperature period of the thermal pulse would be unlikely because of the improbability of such brines being present (Duquette 2004). Because at the time no other plausible brines were known to exist at temperatures above 140°C, the issue of localized corrosion due to brines formed from deliquescent salts seemed to be closed.

A January 2005 letter to the Board from then OCRWM Director Margaret Chu, however, reopened the issue (Chu 2005). The letter suggested that combinations of sodium and potassium nitrates and chlorides salts would deliquesce at atmospheric pressure at temperatures up to and exceeding 200°C, even in the low-relative-humidity environments likely to be present in a Yucca Mountain repository during the thermal pulse. Unlike calcium chloride, these salts are likely to be present in the dusts deposited on waste package surfaces during the preclosure period.

In a December 19, 2005, letter (Garrick 2005c), the Board stated that the technical information available at that time did not seem sufficiently compelling enough to support screening out deliquescence-induced localized corrosion. The Board's opinion was based on the lack of corrosion data above 150°C and the questionable relevance of

[7] The SNF waste form is surrounded by a robust zircaloy or stainless-steel cladding. Some of DOE's SNF is aluminum clad.

Figure 9. A Stylized Drawing of the EBS.



Source: DOE

corrosion-stifling data taken at significantly lower temperatures to corrosion at higher temperatures. To address in greater technical detail the question of whether this combination of salts might cause localized corrosion, the Board convened a two-day workshop in September 2006 (NWTRB 2006d). Twenty-two scientists and engineers, representing the Board, the Project, NRC, the Electric Power Research Institute, the State of Nevada, and Nye County, Nevada, participated in the workshop.

At the workshop, OCRWM reiterated its belief that deliquescence-induced localized corrosion would not occur. Therefore OCRWM would exclude it from the TSPA-LA models that project repository performance over long time periods. The Project based its decision to exclude deliquescence-induced localized corrosion on an event-tree analysis consisting of the following questions (BSC 2005):

1. Can multiple-salt deliquescent brines form at elevated temperatures?
2. If brines form at an elevated temperature, will they persist?
3. If deliquescent brines persist, will they be corrosive?
4. If deliquescent brines are potentially corrosive, will they initiate localized corrosion?
5. Once initiated, would localized corrosion penetrate the waste package's outer barrier?

The Project maintains that if the answer to any of the five questions is "no," then deliquescence-induced localized corrosion will not take place. The Board believes that this five-question approach is reasonable. For that reason, the workshop discussion was structured around the five questions. There seemed to be consensus among workshop participants that the answer to the first question is "yes." There was less consensus on the answers to the other questions, particularly the last two.

Board Findings and Recommendations Related to Deliquescence-Induced Localized Corrosion

The Board published its own findings and conclusions from the workshop in a January 12, 2007, letter to DOE (Garrick 2007a), to which was attached a 10-page report. In the report, the Board noted that there were at least six scenarios in which deliquescence-induced localized corrosion could be excluded, i.e., by which one or more of the five questions above could be answered "no" definitively. The Board also stated that demonstrating an adequate technical basis for screening out deliquescence-induced localized corrosion during the thermal pulse would require (a) determining the nitrate-to-chloride ratios that are inhibitive for the entire range of temperatures at which deliquescent brines may occur on waste package surfaces and (b) confirming the hypothesis that the preferential migration of nitrate ions into the crevice on a waste package is sufficient to maintain nitrate-to-chloride ratios that are inhibitive.

The Board's January 12, 2007, letter and its attached report contained the following additional findings:

- Cumulative damage due to the combined effects of deliquescence-induced localized corrosion and seepage-based localized corrosion merits some analysis.
- Including seepage-based localized corrosion in TSPA-LA while excluding deliquescence-induced localized corrosion is incongruous because the process (localized corrosion) is the same in both cases.
- Deliquescence-induced general corrosion of Alloy 22 should be included in TSPA-LA.
- Anomalies among recent experiments at high temperatures, such as unexpectedly high general corrosion rates and a maximum of general corrosion rate with respect to temperature, require explanation.
- Effects of waste package surface condition on the corrosion of the waste package surface may need more investigation.
- Including deliquescence-induced localized corrosion in TSPA-LA would add to its completeness, robustness, and credibility.

In a follow-up letter to OCRWM dated July 10, 2007 (Garrick 2007c), the Board pointed out that the dust settling on waste package surfaces during ventilation would contain significant amounts of organic materials and that reactions between these materials and nitrate in the dust could affect the amount of nitrate, which inhibits localized corrosion if present in large enough quantities relative to chloride. The Board stated that the Project should analyze the effects of the full range of factors (e.g., organics in dust, acid-gas devolatilization, and radiolysis) that could influence whether inhibitive nitrate-to-chloride ratios persist under repository conditions.

OCRWM responded to the Board's January 12, 2007, and July 10, 2007, letters in a November 20, 2007, letter (Sproat 2007c). Although the Board agrees with some of the points mentioned in the letter, in several instances OCRWM did not address points brought up by the Board. For example, in its January 12 letter, the Board addressed the apparent incongruity of excluding deliquescence-induced localized corrosion while including seepage-based localized corrosion despite the fact that both are the same process, i.e., localized corrosion. In its November 20, 2007, letter, the Project reiterated the differences in the environments between deliquescence-induced and seepage based localized corrosion. The Board concurs that the environments are quite different, but the processes are not. Regardless of whether NRC regulations allow a process to be split in two and one part to be discarded, doing so still remains incongruous.

In addition, the Project refers to components of the dust deposited on waste package surfaces as "reactants" or "limited reactants" in several places in its November 20 letter. Although the Board agrees that many components in the dust could be reactants, it seems that the principal reactants in general or localized corrosion would be either the water component of deliquescent brines or oxygen dissolved in the brines. Both water and oxygen are essentially limitless in supply. If they are consumed by the brine in corrosion reactions, they simply will be replenished rapidly by dissolution or deliquescence. The Board would welcome additional information from the Project about what other components of the dust undergo reactions. Finally, although OCRWM claimed that it had addressed Board concerns about the effects of organic materials on the nitrate-to-chloride ratio in the November 20 letter, the basis for this claim is unclear.

In sum, despite the workshop in September 2006 and the exchange of letters in 2007, the issue of deliquescence-induced localized corrosion, although apparently tractable, remains open.

In sum, despite the workshop in September 2006 and the exchange of letters in 2007, the issue of deliquescence-induced localized corrosion, although apparently tractable, remains open.

Development of a Safety Case

For more than a decade, the Board has held that it is important for OCRWM to develop a structured presentation of the evidence, analyses, and lines of reasoning that can build confidence in the conclusions derived from TSPA (Cohon 1997; Cohon 2000). This set of arguments constitutes what is commonly called a safety case. (See, for example, NEA 2002.)

At the Board's September 27, 2006, meeting in Amargosa Valley (NWTRB 2006e), Project scientists described efforts to assess barrier capability (Swift 2006), discussed cutting-edge scientific investigations (Peters 2006), illustrated how insights can be drawn from natural analogues (Brady 2006), and explained plans for performance confirmation using long-term testing and monitoring (Hansen 2006). Each of these activities can be a key component of a persuasive safety case. Analyses of barrier capability can reveal the extent to which the full system relies on complementary and overlapping capabilities to ensure performance. Cutting-edge science can provide additional insights into the potential performance of the proposed repository's natural and engineered systems. Analogues, such as the site at Peña Blanca in northern Mexico, can identify dominant mechanisms and processes that affect repository performance and can be used to test and evaluate TSPA models. Long-term testing and monitoring can address important uncertainties and provide a basis for improving key process models and performance assessments, thus enhancing confidence in performance projections.

In a December 14, 2006, letter to DOE (Garrick 2006b), the Board endorsed the development of a safety case. For example, the Board pointed out the following:

> Natural analogues of many relevant repository phenomena can be used to challenge and evaluate conceptual and numerical models. Analogues that have existed for periods of time commensurate with the regulatory compliance period proposed for the repository provide excellent cases for testing prevailing conceptual and numerical models of radionuclide transport and isolation.

Natural analogues of many relevant repository phenomena can be used to challenge and evaluate conceptual and numerical models.

But the Board noted in that December letter that OCRWM's safety case has not yet advanced to the point where it could increase confidence in the conclusions derived from TSPA. After the period covered by this report, OCRWM published its safety case. The Board is evaluating that document.

Additional Issues Related to Postclosure Performance of the Proposed Repository System

Waste Degradation and Radionuclide Transport

If the waste package fails, the waste, in its various forms, may begin to degrade. The degradation process is complex, and the fate of the radionuclides is uncertain. The Project's implementation of TSPA, therefore, uses assumptions about radionuclide transport that may often be unrealistic. On several occasions, the Board has observed that obtaining a better fundamental understanding of the entire transport process remains a productive avenue for additional scientific investigation. (See, for example, NWTRB 2006a and Garrick 2006a.) More specifically, research on topics such as secondary mineralization, matrix diffusion, colloid-facilitated transport, hydraulic properties of faults, or other processes that might significantly affect the rate at which dose-contributing radionuclides move from the repository to the environment could yield important insights.

In an August 13, 2007, letter to the Board, OCRWM enumerated the studies that could address the question of radionuclide transport out of the engineered barrier system and into the unsaturated zone below the proposed repository (Sproat 2007a). Although the Project did not disagree with the Board's position that such research could be valuable, it informed the Board that funding levels for this work were reduced in fiscal year 2007 and would be eliminated in fiscal year 2008 because of budget constraints.[8]

Although the variables affecting radionuclide transport, such as temperature, pH, redox state, and ionic strength, can be enumerated, the Board does not minimize the difficulties associated with carrying out the research program it recommends.

[8] OCRWM also described investigations being undertaken related to the incorporation of kinetics of filtration of irreversible colloids in the unsaturated and saturated zones through the "colloid diversity model." The Board realizes that these colloid studies may be interesting, but kinetics of filtration is a complicated problem. Generally, the Board is skeptical about whether treating colloids as chemical species using principles of chemical kinetics and equilibrium is an effective approach.

Nonetheless, the Board restates its view that the key subset of issues associated with radionuclide transport deserves further attention because of the potentially significant effect these phenomena might have on developing realistic estimates of repository performance.

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Realistic Performance Assessments

Radionuclide transport is only one area where the Board believes that OCRWM's estimates of repository performance are unrealistic. In the report published in 2006 (NWTRB 2006c), the Board went to great lengths to explain to OCRWM the importance of eliminating to the greatest extent possible the use of "bounding assumptions," as opposed to realistic distributions of important parameters. Following up on that report, in a December 14, 2006, letter to OCRWM (Garrick 2006b), the Board maintained:

> To increase confidence in repository performance estimates, TSPA should include consideration of all credible and consequential phenomena that significantly affect dose over the period of regulatory compliance…Assessing the realism of TSPA performance estimates can be challenging because some assumptions may be very conservative while others may be nonconservative. The performance-margin analyses identified [by OCRWM] can be very valuable in assessing the magnitude and effects of conservative and nonconservative aspects of TSPA.

In a November 6, 2007, letter (Sproat 2007b), OCRWM defended its use of bounding assumptions, noting that its approach "reflects international experience and Nuclear Regulatory Commission staff perspectives." OCRWM did commit, however, "to complete performance-margin analyses to evaluate the extent of conservatism and/or nonconservatism in the conservative compliance-focused analyses." The Board is pleased that DOE published its performance-margin analyses when it submitted the LA to NRC.

Presence or Absence of Bomb-Pulse Chlorine-36 at the Horizon of the Proposed Repository

Since mid-1996, the Board has followed closely Project investigations to determine whether elevated levels of bomb-pulse chlorine-36 are present at the horizon of the proposed repository. This question is not an academic one. The presence of the isotope in undisturbed rocks at depth would provide incontrovertible evidence that at least some of the water that falls on Yucca Mountain moves rapidly through the unsaturated zone above the proposed repository.

For the last seven years, the Board consistently has urged OCRWM to resolve the apparent disagreement about this issue between Los Alamos National Laboratory, which believed that it found evidence suggesting the isotope's presence, and Lawrence Livermore National Laboratory and the U.S. Geological Survey, both of which failed to find any evidence of elevated bomb-pulse chlorine-36 levels. (See, for example, NWTRB 2001.) The Board also has examined the Project-funded work carried out at the Harry Reid Center for Environmental Studies, University of Nevada, Las Vegas, which identified elevated levels of bomb-pulse chlorine-36 in some samples (NSHE 2006, Cizdziel 2007).

At the Board's January 24, 2007, meeting in Las Vegas, an OCRWM official described the efforts that had been made to reconcile the seemingly divergent findings (Dyer 2007). He

noted that, despite the best efforts of Project scientists, the question of whether elevated levels of bomb-pulse chlorine-36 are present at the proposed repository's horizon remains unanswered. Rhetorically asking where we stand right now, he observed:

> We're not pursuing the chlorine-36 issue further at the moment. We think we've adequately addressed it in the existing state of models that we have. It would appear that perhaps we need some advances in chlorine-36 technology before we can fruitfully use it in this arena.

The Board does not find this argument persuasive. In its April 19, 2007, letter to DOE (Garrick 2007b), the Board noted that the possible existence of bomb-pulse chlorine-36 at depth in Yucca Mountain "remains an outstanding issue whose resolution could greatly enhance confidence in understanding fluid flow within Yucca Mountain." In a response in a November 6, 2007, letter, OCRWM downplayed the disagreement within its scientific team (Sproat 2007b). "The chlorine-36 studies can be viewed as consistent in one important aspect, which is that the studies conducted to date consistently indicate that fast pathways, as indicated by bomb-pulse chlorine, are either rare or non-existent." The Board does not agree with this characterization of the chlorine-36 studies and continues to be puzzled at OCRWM's apparent lack of interest in resolving this question.

Despite the best efforts of Project scientists, the question of whether elevated levels of bomb-pulse chlorine-36 are present at the proposed repository's horizon remains unanswered.

The Crosscutting Issue of Thermal Management

In the Board's *Fifth Report to Congress* (NWTRB 1992), it focused on the crosscutting issue of thermal management—how OCRWM plans to establish the temperature regime under which the repository will operate. It noted that thermal management strongly affects waste acceptance as well as surface and subsurface operations. Thermal management also strongly influences projections of a repository's postclosure performance because EBS corrosion, near-field, and hydrologic models all are temperature dependent. The Board's interest in this subject has not waned over the last decade and a half. The Board recently has seen evidence that the Project has developed a technically sound basis for the thermal criteria and strategy it is using to govern its preclosure and postclosure plans, analyses, and evaluations.

In its previous report (NWTRB 2006c), the Board expressed concerns about the technical basis behind the Project's thermal management strategy. For example, the Board noted that the 11.8 kW/waste package limit appeared to be arbitrary. The Board recommended that OCRWM should "articulate in a transparent way" how it derived that and other criteria. The Board also observed that the implications for thermal management of the TAD canister concept did not seem to have been assessed fully. Finally, the Board was not persuaded that the "thermal-hydrologic models being used to predict postclosure temperature, relative humidity, and water vapor transport within the drifts have a strong technical basis." The Board, therefore, recommended that these models be reviewed by independent experts. Many of the same concerns were repeated in Board letters sent on June 14, 2006 (Garrick 2006a), and April 19, 2007 (Garrick 2007b).

In an August 13, 2007, letter to the Board (Sproat 2007a), the Project agreed with the Board that its thermal management strategy had to be clearly defined. OCRWM described work that was being undertaken, including studies of "thermal decay characteristics of waste and temperature limits at key locations such as the waste package wall

and drift wall." Further, it maintained that the performance specifications for the TAD canister concept, "while ensuring that the thermal performance of the TAD would be consistent with the current postclosure thermal management approach, would provide sufficient flexibility to accommodate alternative thermal management strategies." Finally, the Project informed the Board that "it does not plan to conduct an external review" of the thermal-hydrologic models.

Responding to the Board's August 13, 2007, letter (Sproat 2007b), OCRWM described in greater detail how the TAD performance specification would impose temperature limits for protecting SNF cladding and how it imposes "heat flux vs. canister-wall temperature" constraints. In addition, OCRWM pointed out that several operational approaches are planned for use at the repository as part of the thermal management strategy. These approaches include the following:

- Establishing a broad operational envelope for the emplacement process that satisfies the TSPA constraints.
- Allowing for the aging of TAD canisters to allow decay heat of the TAD canisters to achieve the thermal limits for emplacement.
- Blending low-thermal-power naval SNF and DOE HLW and SNF codisposal packages with commercial SNF to lower the average thermal power in the emplacement drift to meet thermal constraints.
- Accounting for the decay of waste from its date of actual emplacement and the effects of ventilation during the preclosure period.

OCRWM further noted that as part of this strategy, the capability of the surface facilities is considered with respect to the following:

- Designing facilities that can meet potential thermal limits for receipt and handling of the TAD canister.
- Accepting commercial SNF to meet DOE receipt rates.
- Evaluating the capabilities of the facilities for the rates associated with closure of the waste package and subsequent emplacement in the proper thermal arrangement.
- Evaluating the size of the aging facilities with respect to various waste streams.

The Board is encouraged by the progress that OCRWM recently has made in addressing the Board's concerns related to this critical crosscutting issue of thermal management.

Over the last two years, the Board's interactions with OCRWM on the thermal management issue have been productive. The Project is developing an integrated thermal management strategy using the TSM and waste package loading models to evaluate waste acceptance as well as surface and subsurface operations, including emplacement. It is considering different scenarios of assembly age, burnup, and throughput rates using actual assembly power decay rather than a single decay rate based on a theoretical waste stream as it has done in the past. The Board is encouraged by the progress that OCRWM recently has made in addressing the Board's concerns related to this critical crosscutting issue of thermal management.

Site Visits by the Board

Sweden and Finland

On August 21–25, 2006, a delegation of the Board met with representatives of the Swedish and Finnish nuclear waste disposal programs for spent nuclear fuel and visited a number of their facilities. The visit included tours of their proposed sites for deep geologic disposal and surface and underground research facilities; a tour of Sweden's canister laboratory and central long-term storage facility for SNF; a tour of one of Finland's two permanent repositories for LLW and ILW waste; a meeting with elected representatives from one of the two proposed sites for a final repository in Sweden; meetings with the regulatory authorities of both countries; discussions with the leadership and scientists/engineers involved in managing and researching disposal methodologies in both countries; and a meeting with representatives of the Swedish Council for Nuclear Waste (formerly KASAM), the Board's counterpart in Sweden.

Idaho National Laboratory

On June 6–7, 2007, a delegation of the Board visited the INL site and the INL operations office in Idaho Falls. The primary purposes of the visit were to observe and discuss activities having to do with the management and disposal of SNF and HLW.

A large number of activities directly related to Yucca Mountain are being conducted at the INL site by the INL operations office. All of the SNF from U.S. Navy aircraft carriers and submarines comes to the Naval Reactors Facility for inspection, storage, and eventual packaging and shipment to a repository for disposal. A reprocessing facility operated until 1992, and all the HLW from those operations remains stored there in tanks or silos in liquid or solid (calcine) form, respectively. Eventually, this HLW has to be treated and packaged for shipment to a repository. In addition, a large amount of DOE-owned SNF from research, defense, and other programs is stored on the INL site. Eventually, all this material will go to a deep geologic repository for disposal. INL is in charge of the entire disposal program for DOE-owned spent fuel and therefore is responsible for characterizing and categorizing such spent fuel and defining plans for its disposal at Yucca Mountain, including designing and creating prototypes of the canister for containing the spent fuel. Finally, INL is developing criticality-control materials for disposal, performing corrosion tests on the materials, and developing robotic welding and inspection equipment to be used at Yucca Mountain.

Board Plans for 2008

When Congress authorized the establishment of the NWTRB in the NWPAA, it included a provision stating that the Board would cease functioning no later than one year after the date on which the Secretary of Energy begins disposal of HLW or SNF in a repository (NWPAA 1987). DOE's submittal of the LA to NRC will not change the Board's congressionally mandated role. In particular, the Board will continue to conduct technical evaluations of DOE's progress in understanding how the engineered and natural systems of the repository would work together to isolate radionuclides and how realistic DOE's performance estimates are. The Board also will review DOE's repository and surface facility designs and DOE's program for managing spent nuclear fuel and high-level radioactive waste before closure of the proposed repository. In conducting its evaluation, the Board

will maintain its focus on "technical validity." The Board leaves to NRC the judgment of whether the arguments and predictions contained in the LA comply with and satisfy that agency's regulations.

In 2008, the Board intends to hold three public meetings to ensure that it is being kept current on OCRWM's technical and scientific activities. In addition, several more fact-finding meetings will take place. The Board also plans to pursue with the Project the open issues that have been enumerated above.

Finally, the Board has initiated a series of extensive systematic analyses looking both at the technical bases used by OCRWM to project postclosure performance of the proposed repository at Yucca Mountain and at the preclosure operations of the entire waste management system. As appropriate, the Board will communicate the findings and recommendations that derive from those analyses later this year.

Abbreviations and Acronyms

Board	U.S. Nuclear Waste Technical Review Board
CRCF	Canister Receipt and Closure Facility
DOE	U.S. Department of Energy
DPC	dual-purpose cask
EBS	engineered barrier system
EIS	environmental impact statement
EPA	U.S. Environmental Protection Agency
HLW	high-level radioactive waste
IHF	Initial Handling Facility
INL	Idaho National Laboratory
LA	License Application
NEA	Nuclear Energy Agency
NRC	U.S. Nuclear Regulatory Commission
NWPAA	Nuclear Waste Policy Amendments Act of 1987
NWTRB	U.S. Nuclear Waste Technical Review Board
OCRWM	Office of Civilian Radioactive Waste Management
PCSA	Preclosure Safety Analysis
Project	Yucca Mountain Project
QA	quality assurance
RF	Receipt Facility
SAR	Safety Analysis Report

SCC	stress-corrosion cracking
SEIS	supplemental environmental impact statement
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
TAD	transportation-aging-disposal
TSM	Total System Model
TSPA	Total System Performance Assessment
USGS	U.S. Geological Survey
WHF	Wet Handling Facility

Glossary of Terms

Alloy 22 A nickel-chromium-molybdenum alloy proposed for use as the material of construction for the waste package's outer wall.

alluvium Clay, silt, sand, gravel, or similar detrital material deposited by running water.

analogue (analog) A phenomenon that can provide information on or add understanding to aspects of repository performance. Analogues are of two types: natural and anthropogenic. Natural analogues occur through natural phenomena. Anthropogenic analogues result from human activity. An "archaeological analogue" is an anthropogenic analogue resulting from the activities of ancient cultures.

barrier A natural or engineered system that prevents or mitigates the movement of radionuclides toward the accessible environment.

brine A concentrated solution of one or more salts in water.

bomb-pulse See **chlorine-36.**

bounding analysis Extreme parameter estimates used to project repository performance.

burnup A measure of reactor fuel consumption expressed as the percentage of fuel atoms that have undergone fission, or the amount of energy produced per unit weight of fuel.

cladding The outer layer of a nuclear fuel rod.

chlorine-36 (36Cl) A long-lived radioactive isotope of chlorine produced by irradiation of natural chlorine, argon, or other materials by cosmic rays or neutrons. Atmospheric testing of nuclear weapons in the 1950's temporarily increased concentrations of chlorine-36. The resulting "bomb-pulse" levels of chlorine-36 can sometimes serve as a tracer to determine how rapidly precipitation from the 1950's has moved through soil and rocks such as those present at Yucca Mountain.

colloid A state of subdivision of matter in which the particle size varies from that of true "molecular" solutions to that of coarse suspensions with the diameter of the particles lying between 10^{-7} and 10^{-5} centimeters.

conservative Projections of repository performance using parameters and models that systematically underestimate the system's ability to isolate and contain waste.

corrosion A destructive attack of a material by chemical or electrochemical interaction with its environment.

criticality The condition in which a fissile material sustains a nuclear reaction. Criticality occurs when the number of neutrons present in one generation cycle equals the number generated in the previous cycle.

deliquesence The absorption of atmospheric water vapor by a solid salt to the point where the salt dissolves into a saturated solution.

dose See **radiation dose**

drift An underground opening or tunnel that is used for access/egress, to facilitate repository construction, ventilation, and transportation and emplacement of nuclear waste.

drip shield Barriers placed over and around waste packages to divert water from the packages and deflect falling rocks from impacting the waste package.

engineered barrier system (EBS) The constructed components of a disposal system designed to retard or prevent releases of radionuclides from the underground facility. Such components include waste forms, fillers, waste containers, shielding placed over and around such containers, and backfill materials.

fault A plane in the earth along which differential slippage of the adjacent rocks has occurred.

fuel rod An engineered structure that consists of a rod or tube, typically made of zircaloy, into which fuel material, usually in the form of uranium oxide pellets, is placed for use in a reactor. Many rods or tubes, which are mechanically linked, form a fuel assembly or fuel bundle.

geologic repository A facility for disposing of radioactive waste in excavated geologic media, including surface and subsurface areas of operation and the adjacent part of the natural setting.

groundwater Subsurface water as distinct from surface water.

high-level radioactive waste (HLW) Highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in concentrations above levels specified in regulations. Any other highly radioactive material that the Nuclear Regulatory Commission, consistent with existing law, determines requires permanent isolation by disposal in a geologic repository.

infiltration The flow of a fluid into a solid substance through pores or small openings; specifically, the movement of water into soil or porous rock.

invert The natural or engineered floor configuration of a tunnel or an underground opening.

License Application (LA) A document submitted to the Nuclear Regulatory Commission containing general information and a safety analysis for certain nuclear facilities such as a nuclear power plant, a geologic repository, and a spent-fuel storage facility. A license application must be approved before the facility is constructed and before it can be operated.

line-load Two distinctly different emplacement strategies for waste packages within an emplacement drift. A line load refers to placement so that the waste packages are virually end-to-end or nearly touching. Point load refers to placement such that the packages are separated by a least 2m.

localized corrosion Corrosion that takes place at discrete sites—for example, in waste package crevices.

matrix The solid framework of a porous system.

matrix diffusion The migration of higher concentrations of dissolved chemicals from more permeable zones to zones that are less permeable and that have lower concentrations of the same dissolved chemicals.

multiple lines of evidence Varied methodological approaches used in combination to infer the behavior of the repository system (or its major components) for extended time periods. Examples of individual methods include analogues, simplified calculations, and arguments based on defense-in-depth.

natural barriers Attributes of the earth that tend to isolate radionuclides from the human-accessible environment.

near field A zone that typically extends one diameter outward from the tunnel wall. In that zone, coupled thermal, hydrological, mechanical, and chemical processes are expected to occur.

Nuclear Waste Policy Act (NWPA) The federal statute enacted in 1982 that established the Office of Civilian Radioactive Waste Management and defined its mission to develop a federal system for the management and geologic disposal of commercial spent nuclear fuel and other high-level radioactive wastes, as appropriate. The Act also specified other federal responsibilities for nuclear waste management, established the Nuclear Waste Fund to cover the cost of geologic disposal, authorized interim storage until a repository is available, and defined interactions between federal agencies and the states, local governments, and Indian tribes.

Nuclear Waste Policy Amendments Act (NWPAA) The federal statute enacted in 1987 that amended the Nuclear Waste Policy Act by limiting repository site-characterization activities to Yucca Mountain, Nevada; establishing the Office of the Nuclear Waste Negotiator to seek a state or Indian tribe willing to host a repository or monitored retrievable storage facility; creating the Nuclear Waste Technical Review Board; and increasing state and local government participation in the waste management program.

overpack A container used for transporting and/or storage of canisters that do not meet the applicable NRC or Department of Transportation requirements.

percolation flux The movement of water through the repository horizon per unit area per unit time.

performance assessment A complex computer-based analysis that projects how well the entire repository system will isolate and contain waste and what the human health consequences will be if waste reaches the biosphere.

performance confirmation The tests, experiments, and analyses that are conducted to evaluate the accuracy and adequacy of the information used to determine with reasonable assurance that the repository performance objectives for the period after permanent closure will be met.

performance-margin analysis A type of performance analysis in which particular parameters are varied to obtain insights into their effect on waste isolation and containment and human health.

performance specification A set of instructions that outlines the functional requirements for a specific component or process.

postclosure The time after the closure of the geologic repository.

preclosure The time before and during the closure of the geologic repository.

process models Conceptual and mathematical models of a particular process (e.g., unsaturated-zone flow) that reflects the phenomena of interest. The models then can be abstracted (simplified) for use in performance assessments.

radiation dose The amount of energy deposited in a unit of mass of a material. In addtion, several modified doses, including dose equivalent and effective dose, that more closely approximate the biological harm to humans from exposure to ionizing radiation.

radionuclide An atomic nucleus that is radioactive.

radionuclide migration or radionuclide transport The movement of radioactive materials through rock formations, typically in water.

repository See **geologic repository**

saturated zone The part of the Earth's crust in which all empty spaces are filled with water.

seismic Pertaining to an earthquake or an earth vibration.

source term The compositions and the kinds and amounts of radionuclides that make up the source of a potential release of radioactivity from the engineered barrier system to the host rock.

spent nuclear fuel (SNF) Fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by chemical reprocessing.

SNF assembly See **fuel rod.**

thermal-management strategy A plan for maintaining the temperatures of the waste form, the cooling system, the facility, and the natural and engineered barrier systems within design limits.

thermal pulse The period of approximately one thousand years immediately following repository closure during which temperatures on the waste package surface can rise to more than 150°C, according to the Department of Energy's current repository design.

thermohydrology The study of coupled water and heat flow.

Total System Model (TSM) A tool for analyzing the linkages, interactions, and synergies between waste acceptance, transportation, and the repository. A model capable of integrating and analyzing the waste management system performance, alternative system solutions, and program and policy impacts.

Total System Performance Assessment (TSPA) Term used by the U.S. Department of Energy to describe the particular performance assessments conducted to determine whether the proposed Yucca Mountain repository complies with the relevant regulatory requirements for waste isolation and containment and protection of human health.

transparent Easy to detect or observe. The use of clear language and easily understood concepts and/or assumptions to arrive at credible, traceable, and logical conclusions.

unsaturated zone Layers of rock in which some, but not all, of the empty spaces are filled with water.

waste form The radioactive waste materials and any encapsulating or stabilizing matrix. Examples include used reactor fuel elements and borosilicate glass "logs."

waste form degradation The result of chemical and physical changes that occur when the waste form is exposed to the local environment.

waste management system All elements of the system involved in the management of radioactive wastes.

waste package The waste form, any fillers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container.

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