Chapter 3

Engineered Barrier System

I. Introduction

The proposed repository consists of natural geologic barriers and engineered barriers. All of the engineered barriers together constitute the engineered barrier system (the EBS). The EBS can be divided into two interrelated components: the underground facility[1] and the waste packages.[2] The two components are discussed in this chapter.

II. Underground Facility

Before repository closure, the underground facility provides the space for emplacing waste packages, monitoring them, retrieving them if necessary, and conducting performance confirmation testing. After closure, the underground facility can contribute to performance (the ability of the repository system to contain and isolate waste) by providing a favorable, or at least a nonaggressive, near-field environment for the waste packages.

The current design of the underground facility reflects a 1995 study (CRWMS 1995a) and a DOE decision to focus on designs with high areal mass loading (i.e., 80-100 metric tons of uranium [MTU][3] per acre). The decision resulted in large part from the hypothesis that the heat from the decay of the radioactive waste could provide an above-boiling environment for waste packages for up to thousands of years and that such an environment would result in low humidity, low waste package corrosion, and therefore low waste package failure rates. A significant effect of the decision was that the entire 70,000 MTU specified by Congress as the capacity limit for the first geologic repository could be accommodated in the approximately 1,200-acre block under Yucca Mountain nominally bounded by the Ghost Dance fault on the east and the Solitario Canyon fault on the west.

The current (reference) design of the underground facility results in peak temperatures of nearly 200ºC in the tunnel (drift) walls and 250ºC on a waste package's outer surfaces. Throughout this chapter, the current design of the underground facility is referred to as the "hot" repository design to distinguish it from an alternative cooler repository design in which peak temperatures would be much lower.

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[1] "Underground facility" means the underground part of a geologic repository where spent nuclear fuel and high-level wastes are emplaced, excluding shafts, ramps, boreholes, and their seals.

[2] "Waste package" means the radioactive waste materials and any encapsulating and stabilizing matrix, as well as any containers, shielding, packing, and other absorbent materials immediately surrounding an individual waste container (10 CFR 60). The term does not mean only the waste container. Except where otherwise stated, the discussion in this chapter is based on the current (reference) designs of the underground facility and the waste packages.

[3] One MTU is the amount of spent fuel that contained 1,000 kilograms of uranium before irradiation.

III. Current Design of Underground Facility[4]

A. Facility Configuration

The block for the underground facility would occupy about 1,200 acres under Yucca Mountain, the actual emplacement area being about 800 acres. The underground facility would consist of about 100 parallel emplacement tunnels that run roughly east to west. This orientation results in the most stable tunnels because the tunnels are at least 30 degrees from the presumed dominant joint orientations. The emplacement tunnels would be approximately 1,200 meters long and 5.5 meters in diameter and would connect at each end to a 7.62-meter-diameter tunnel that runs along the perimeter of the emplacement area. The existing north and south ESF ramps would connect the perimeter tunnel to the surface.

The waste-emplacement tunnels would have precast-concrete floor and ground-support segments. Ventilation during construction and operations would be provided by the north and south access ramps and two shafts connecting to a central north-south exhaust tunnel below the underground facility. This system would be ducted to the center of each emplacement tunnel. The ventilation system would provide separate air-flow systems for underground facility loading and construction. It would be capable of rapidly cooling a single waste-emplacement tunnel at high air-flow rates if waste packages need to be removed, for example for tunnel maintenance and repair. In this hot repository design, each emplacement tunnel would be closed immediately after it is filled, and ventilation of the closed tunnel would be reduced to a very low rate until repository closure. At repository closure, this limited ventilation would cease.

After all emplacement tunnels are filled, the underground facility would remain accessible for at least 50 years for monitoring and performance confirmation. (Recently, the DOE suggested changing the reference design so that the underground facility would remain accessible and observable for up to 300 years [Barrett 1998]). The underground facility eventually would be closed and permanently sealed.

B. Thermal Management

The areal mass loading of the underground facility would be determined by the contents of the waste packages and the spacing of the packages within the underground facility. Temperatures within the underground facility would depend largely on the areal mass loading and the degree of ventilation. As spent-fuel assemblies are received at the aboveground facilities, they would be placed in waste packages. The waste packages then would be moved to the underground facility for emplacement, generally in the same order as received at the aboveground facilities. No provision would be made for aging or mixing assemblies to lower temperatures or to obtain a more-uniform temperature distribution.

The key hypothesis of the hot repository design is that decay heat from the radioactive waste would create above-boiling temperatures that would keep liquid water away from waste packages. This low-humidity waste package environment could persist for several thousand years.[5] However, water that vaporizes in the rock would condense in cooler regions of rock farther away, and some of this condensate could flow back onto some of the packages.[6] The resulting hot and wet conditions could exacerbate waste package corrosion[7] and mobilization of radionuclides in the waste. In addition, as the underground facility eventually cools and waste package temperatures fall below boiling, hot and wet

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[4] The design information in this section is taken primarily from CRWMS 1997a and CRWMS 1997b.

[5] The duration of above-boiling temperatures for the hot repository design would be determined largely by the areal mass loading of the underground facility, which is specified to be 85 MTU per acre; the age of the spent fuel at emplacement; and the percolation flux through the repository horizon. A very rough rule-of-thumb is that 1 MTU of 20-year-old commercial spent fuel generates 1 kW of decay heat. Decay heat decreases with age.

[6] See Simmons and Bodvarsson 1997 for more discussion of this issue.

[7] Such "refluxing" of condensate could be of particular concern if waste package materials are susceptible to pitting corrosion at temperatures marginally below boiling.

conditions can be expected. Uncertainties about how hydrologic and mechanical conditions in the surrounding rock will evolve over time make it difficult to predict the waste package environment and, thus, the ability of the waste packages to contain radioactive waste.

C. Tunnel Stability (Rockfalls and Tunnel Collapse)

The natural temperature of Yucca Mountain at the repository horizon is approximately 25°C. If the average temperature of a waste emplacement tunnel rises to 160°C (CRWMS 1997a) in the hot repository design, modeling indicates that the tunnel would expand vertically 8 to 10 mm while shrinking horizontally the same amount (Elsworth 1998). The thermal stresses causing these deformations could increase the probability of rockfalls or tunnel collapse.[8] Tunnel collapse may be thought of as the culmination of many rockfalls.

In the hot repository design, rock temperatures would peak about 50 years after waste is emplaced. The period of maximum thermal stress on the tunnel walls is thought to be during the heat-up phase and when the rock is at or near its peak temperature. If the underground facility remains accessible and observable for about 300 years, the temperatures of the rock will have decreased to around 120°C, and the rock will have passed through its period of highest stress. By then, if the rock is observed to be stable, it likely will remain stable indefinitely. If it has failed, repairs might be possible before closure of the underground facility.

Tunnel stability is important for waste package performance. For example, rocks falling from the roof of a tunnel could break through the wall of a waste package already thinned by corrosion. An analysis shows that a 350-kilogram rock falling 2.4 meters could cause the failure of a waste package that has lost 85 percent of its outer-wall thickness because of corrosion (CRWMS 1996, Barnard 1998). Even if a falling rock is not heavy enough to cause waste package failure, it could dent the waste package and the resulting depression could collect water. This situation, together with residual stresses in the struck area, could accelerate local corrosion. Rockfalls make predicting the amount and timing of water contacting a waste package more difficult because the rockfalls affect the characteristics of the rock in the tunnel roof (thereby making seepage more difficult to estimate) and affect the way that seepage is distributed before it contacts a package.

IV. Alternative Underground Facility Designs

Evaluations of alternative underground facility designs are needed, especially those that may provide at least the same level of performance with reduced uncertainty. Many aspects of underground facility design may affect performance, including tunnel diameter, waste emplacement mode (e.g., in tunnel openings, walls, or floors), degree of ventilation, and use of backfill or drip shields. For example, the negative effects and uncertainties associated with rockfalls and tunnel collapse might be reduced, or possibly eliminated, by changes in underground facility design. The following are examples of such changes:

- Using smaller tunnel diameters, which would lead to greater tunnel stability and a shorter distance for rocks to fall.

- Using backfill, which would cushion waste packages against rockfalls.

- Adopting a cooler repository design, which would reduce thermal stresses.

- Using fillers in waste packages, which would make them more resistant to penetration and denting.

One of the most important aspects of design is repository temperature. A cooler design may have the advantage of greater certainty about the hydrologic

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[8] New methods for keyblock analysis being developed by the Yucca Mountain project may permit probabilistic assessments of tunnel stability, spatial variability of rock block sizes, and frequency of rockfalls.

and mechanical behavior of the rock surrounding tunnels and could reduce the rates of waste package corrosion and radionuclide mobilization from the waste. Lower peak temperatures also would reduce the degree of coupling between the thermal and the hydrologic, chemical, and mechanical processes—a major source of uncertainty in estimating performance. Lower temperatures could extend waste package life by preventing (or at least reducing) the period when conditions are both hot (near boiling) and wet—conditions known to exacerbate corrosion of waste package materials.

Underground facility temperatures may be reduced by aging the spent fuel before placing it in the underground facility, by using smaller waste packages and placing them farther apart to reduce the areal mass loading, by continuously ventilating the waste emplacement tunnels before underground facility closure (Danko 1997), or by a combination of the three procedures. A cooler underground facility design could use ventilation to keep the walls of emplacement tunnels below boiling, thereby reducing the degree to which water vaporizes near the wastes and moves to cooler regions where it would condense. Removal of heat by ventilation also would permanently remove some water through evaporation into the normally very dry desert air. By limiting temperatures, this design would simplify predictions of hydrologic, mechanical, and chemical conditions in nearby rocks.

There may be offsetting disadvantages of increased ventilation, more-complex fuel-aging procedures, or increased repository area. Analyses of alternative designs should illuminate the relative merits of hot and cooler designs.

V. Waste Package Design

High-level radioactive wastes include spent pressurized-water reactor fuel, spent boiling-water reactor fuel, spent research reactor fuel, and waste from reprocessing that has been solidified into glass logs. Regardless of whether such waste is measured on the basis of current or future radioactivity, more than 90 percent of the waste is spent fuel from commercial nuclear power reactors. Thus, the following discussion of the uncertainties in the long-term performance of waste packages in deep geologic repositories focuses on commercial spent fuel.

In the current design, a waste package containing spent commercial fuel has four distinct barriers. From the outside in, they are (1) a 10-cm-thick carbon-steel outer wall; (2) a 2-cm-thick nickel-alloy inner wall; (3) cladding, usually zircaloy, surrounding the spent fuel; and (4) the spent fuel itself, which consists of degraded uranium oxide ceramic pellets that contain small amounts of fission products and actinides. In general, the four waste package barriers would fail sequentially from the outside in. That is, the processes leading to failure of an inside barrier would not begin until the barrier immediately outside of it is penetrated. However, certain disruptive processes or events, such as falling rocks, could cause more than one barrier to fail simultaneously.

A. Environmental Conditions for Waste Packages

The external environmental conditions for the waste packages are the pressures, temperatures, and compositions of the gases, liquids, and solids that contact the waste packages *before such gases, liquids, and solids are chemically modified by interaction with the waste packages.* Waste packages emplaced in an underground facility at Yucca Mountain would undergo a range of external environmental conditions that would affect the rate of corrosion of the packages.

The range of external environmental conditions for emplaced waste packages is reasonably well bracketed. The gas pressure outside the waste packages would be approximately atmospheric at all times. For the current hot repository design, temperatures on the outer surfaces of the waste packages would fall within the range of 25°C to 250°C, and the relative humidity of the gas phase surrounding the waste package would range from near 0 percent to 100 percent. For a cooler underground facility design, temperatures on the outer surfaces of waste packages would fall within the range of 25°C to 150°C, and the relative humidity of the gas phase surrounding the waste package would still range from near 0 percent to 100 percent.

The composition of water in the pores of the rock in the UZ is similar to the composition of water in well

J-13 in the SZ, the main source of water for the project. However, principally because of thermal effects, water that drips on waste packages is unlikely to have the same composition as that of undisturbed pore water. Pore water in the rock near the tunnels would evaporate, leaving salts behind. Evaporated water would condense in cooler zones farther away from the tunnel walls. Conceivably, some of the water could run back into the tunnels through high-permeability zones shortly after condensing and before it has enough time to become saturated with salts. This water could be as dilute as nearly pure condensate, or it could approach J-13 water in composition. On the other hand, hot condensate could dissolve soluble salts, resulting in solutions that are more concentrated than J-13 because the solubilities of most salts increase with temperature. Solutions also could become more concentrated simply by dripping onto a hot waste package and evaporating.

Although the *range* of environmental conditions outside an emplaced waste package is reasonably well understood, *when* a given waste package would be in one part of the range or another and for *how long* are much less well understood. For example, although water would drip onto some of the waste packages some of the time, which packages would be contacted by dripping water and when they would be contacted are not known.[9] The ability to predict the timing and distribution of dripping water is important because waste packages will corrode faster if they are dripped on and, except for gaseous radionuclides, water is necessary for transporting radionuclides away from a waste package and toward the environment that is accessible by humans.

Contact between liquid water and waste packages is necessary for significant corrosion rates to occur. Predicting corrosion with reasonable confidence requires knowledge not only of the waste package materials and external environmental conditions but also of the modified environmental conditions that would evolve on (or inside) waste packages as a result of interactions among waste package materials and corrosion reactions, corrosion products, radiolysis,[10] and external environmental conditions. The modified environmental conditions on a package can vary widely over just a few millimeters, depending on where drips contact the package, the presence or absence of crevices, and the amount of corrosion that has occurred already.

A particular concern about the modified environmental conditions is the highest concentration of ferric chloride and the lowest pH to which the inner wall and waste form may be exposed. The inner wall and waste form can degrade rapidly in environments having high ferric chloride concentrations and low pH. The rate of degradation generally increases with temperature. Currently, there is considerable uncertainty about the chemical compositions of the modified environmental conditions. This uncertainty could be reduced significantly by laboratory experiments aimed at defining the range of modified environmental conditions. Calculations using existing thermodynamic models (e.g., the computer program, EQ3/6 [Wolery and Daveler 1992]) could help in guiding, interpreting, and verifying the experiments.

B. Waste Package Barriers

The four distinct barriers provided by a waste package containing commercial spent fuel are discussed below, from the outside in.

1. Carbon-Steel Outer Wall

The carbon-steel alloy for the outer wall contains more than 98 percent iron; carbon and other alloying elements make up the rest. Metallic iron is not thermodynamically stable. It eventually combines with

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[9] As discussed in the chapter on the UZ, modeling of seepage into drifts has been attempted. Not unexpectedly, modeling results are very sensitive to local percolation flux and local rock properties, both of which are difficult to predict.

[10] As the radioactive waste decays, it generates ionizing radiation. The interaction of ionizing radiation with fluids around it is called “radiolysis.”

other substances in the environment (e.g., oxygen, water, sulfur) by means of corrosion processes to return to a condition resembling that of the ores from which it was extracted. Corrosion wastage of the outer walls of some of the waste packages is very likely within the extremely long expected time frame for the underground facility. The operating corrosion processes and the rate at which they happen would be determined by the immediate package environment. Modes of corrosion of the outer wall (and when and where they are likely to prevail) are discussed below.

a. Corrosion Modes

Iron alloys (i.e., steel) in contact with hot, dry gas may corrode through direct formation of metal oxides on the alloy surface. This corrosion mode is the most likely while package wall temperatures are well above boiling and in the absence of water dripping on the hot packages. Assuming the current hot repository design, low-relative-humidity conditions are hypothesized to persist for thousands of years for the waste packages located close to the center of an underground facility at Yucca Mountain (Stacey et al. 1997). Extensive corrosion-performance data on these service conditions are in the literature. At the temperatures and gas compositions projected for hot and dry packages, oxidation should be relatively uniform over the metal surface and very slow, resulting in negligible wastage as long as the conditions are maintained.

Iron alloys in contact with liquid water corrode by ionic dissolution of the metal into the water (corrosion products, such as rust, form afterward). Direct dripping of water on a package is not needed for this process; water may be present in the form of a very thin layer on the metal surface, even above the nominal boiling temperature if the relative humidity becomes high enough. A thin water layer is certain to form as the temperature becomes lower and humidity increases later in the life of the underground facility. Corrosion rates under those conditions can be predicted approximately from existing literature, and experiments are under way to obtain additional information,[11] but penetration of the outer wall by this type of process is expected to require times on the order of a thousand years or more.

Far more severe corrosion results if carbon steel is in direct contact with dripping water (as in a package directly below a seepage point) or is surrounded by a porous medium made moist by the surrounding environment (as in a package in a crumbling tunnel or a package surrounded by porous earlier corrosion products). Abundant information is in the literature on the corrosion rate of steel in direct contact with natural waters at various temperatures. In addition, laboratory tests measuring the corrosion rate of carbon steel (both immersed in water and in the vapor zone) at conditions approximating those expected at Yucca Mountain have been under way for nearly 2 years and are scheduled to continue for several more years (Gdowski 1995, McCright 1995, Stahl 1997). The available data indicate that the outer walls of packages exposed to these corrosion regimes are likely to be penetrated on the order of a few hundred years after water begins contacting them.

The effects of corrosion can be aggravated if the corrosion becomes strongly localized, as in the phenomenon known as *pitting corrosion*. Corrosion pits conceivably could penetrate a thick metal wall much more quickly than generalized corrosion can. In carbon steel, pitting corrosion is promoted if aggressive agents, such as chloride ions (as in concentrated pore water), are present and the pH of the surrounding water is about 10 or higher. This suggests a potentially adverse effect of using concrete extensively for underground facility construction, because concrete leachates could significantly elevate the pH of the seepage water.

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[11] Research on thermogravimetric microbalance for determining corrosion rates of metals covered by thin water films has been under way at Lawrence Livermore National Laboratory for several years (Gdowski 1995).

b. DOE Approach

The TSPA-VA outer-wall corrosion model recognizes the modes indicated above and incorporates corrosion rates for each case that are within generally accepted levels. Long-term laboratory corrosion tests seem to be confirming the values adopted from earlier literature reviews (Stahl 1997). The model also includes a provision for the onset of pitting corrosion, using plausible aggravation factors. Continuing the work on reducing uncertainty about these projected rates is important.

The TSPA-VA model divides the package surface into individual elements (patches). Most important is the predicted number of patches that are subject to direct water contact (because the corrosion modes for the other patches are much less severe). Thus, much of the uncertainty of the present model projections derives from uncertainty in predicting the spatial and temporal distribution of water dripping on the waste packages. Extreme conditions, such as a concentrated jet of water impinging on a hot package, could even trigger an erosion-corrosion mode not considered in the discussion above that might result in penetration of the outer layer in as little as a few years (WPDEE 1998). Reducing uncertainty about seepage distribution (as discussed in the UZ chapter) is therefore crucial to a more reliable projection of outer-wall performance.

Other issues that warrant attention are performing a more detailed analysis aimed at predicting the chemistry of the water contacting the package, especially the elevated pH after interaction of underground facility water with structural concrete, and taking into account the neutralizing capacity of carbon dioxide (CO_2). Continuation of work by the DOE along these lines (Sassani et al. 1997) could help reduce uncertainty.

2. Nickel-Alloy Inner Wall

The material for the inner wall is a chromium-rich nickel-base alloy with the designation Alloy 22.[12] Nickel, chromium, and other important alloy components are not thermodynamically stable under the expected repository conditions. Instead, the alloy derives its corrosion resistance from the phenomenon of *metallic passivity*. A thin film (sometimes only a few atomic layers deep) forms on the surface of the alloy and separates the reactive metal from the surrounding environment. When this passive film is stable, the alloy becomes extremely corrosion resistant.

Interim TSPA-VA results made available to the Board show that the proposed Alloy 22 inner wall is a very important barrier for the first 10,000 years of a repository's lifetime and perhaps for many more tens of thousands of years. Therefore high confidence in performance predictions for this wall is important.

a. Present State of Knowledge

Prediction of the performance, over repository time scales, of corrosion-resistant engineering alloys that owe their resistance to the formation of passive films cannot be backed by direct experience, because these alloys have been in use for a few decades at most. Nevertheless, extensive knowledge of fundamental mechanisms for the formation and breakdown of passive films has been developed over the past half-century. Research based on that knowledge has shown that under certain severe conditions, passivity can be compromised even for highly corrosion-resistant alloys, such as Alloy 22, and that rapid corrosion ensues (Haynes 1997).

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[12] In the last 2 years, the reference material for the inner wall has been changed to progressively more-corrosion-resistant materials: from Alloy 825 to Alloy 625 to Alloy 22. The basic composition of Alloy 825 (in weight percent) is Ni 42, Fe 28, Cr 21, Mo 3, Cu 2, and Ti 1; of Alloy 625, Ni 61, Cr 21.5, Mo 9, Nb 3.6, and Fe 2.5; and of Alloy 22, Ni 56, Cr 22, Mo 13, Co 2.5, W 3, and Fe 3.

Research also has shown that under less severe conditions (which include even highly concentrated J-13-type water near boiling), those alloys remain passivated and have extremely low corrosion rates, on the order of 0.1 micrometer per year (Stahl 1997). These less severe conditions are prevalent in present projections of the repository environment. However, partly due to lack of long-term direct experience and partly due to uncertainties about the severity of the modified environmental conditions that corrosion-resistant alloys might be exposed to in Yucca Mountain, the ability to demonstrate that these alloys would survive many thousands of years in a repository remains a matter of debate within the materials community.

Combinations of ferric and chloride ions are known to generate low-pH environments that cause passivity breakdown in corrosion-resistant alloys. These ionic combinations conceivably could result from the presence of corrosion products of the carbon-steel outer layer and chloride ions concentrated by evaporation of seepage water. Research could be conducted to determine by experiment and thermochemical calculations whether the present package design could easily generate such an environment. The outcome of that research would indicate whether the present waste package design presents the danger of failing after a relatively short time (perhaps hundreds of years) or whether the package has a chance of surviving tens, or hundreds, of thousands of years.

If research reveals that the carbon-steel corrosion-allowance metal could create such an aggressive environment, a modified waste package design could be developed with current technology to prevent the problem. For example, a modified design could use the nickel alloy on the outside and the carbon steel on the inside to retain mechanical strength. Another approach could involve using redundant layers of diverse corrosion-resistant alloys, such as Alloy 22 and a titanium alloy (another material relying on metallic passivity for its corrosion performance). Other potentially large sources of ferric ions, such as the tunnel steel sets and the steel reinforcement of the concrete tunnel walls, would need to be eliminated.

Even in the absence of external ferric ion sources, localized depassivation of high-performance alloys can occur by pitting or *crevice corrosion* if aggressive microenvironments form at the metal surface. This may occur, for example, at contacts between the metal and tunnel debris; at metal-metal openings, including surface rolling imperfections; and at places where the package rests on its pedestal. Another form of localized failure is *stress-corrosion cracking*,[13] which could affect the area of the final closure weld of the package or other points of unrelieved stresses.

The information available to date (Roy et al. 1997) suggests (but does not ensure) that Alloy 22 has little susceptibility to these forms of corrosion under the expected repository service conditions, pending resolution of the issue on chloride and ferric ions mentioned earlier. Titanium alloys can be attacked by fluoride ions (Dillon 1998), which are present in small amounts in the rock pore water and could become concentrated from evaporation. Otherwise, titanium alloys also appear to have very low susceptibility to localized corrosion under the anticipated service conditions.

b. DOE Approach

The TSPA-VA model of a corrosion-resistant alloy wall takes into account the modes of corrosion indicated above. Like the outer wall, the inner wall surface in the DOE model is divided analytically into patches with or without direct water contact. Corrosion of the patches proceeds by uniform dissolution (at rates assumed to be comparable to those observed in passive metal laboratory tests) or by localized (pitting) corrosion for a small fraction of the patches. The present choice of distribution of corrosion-rate values for uniform corrosion reflects input from the technical literature that includes some cases showing relatively high corrosion rates (McNeish 1998a). As a result of that choice, uniform

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[13] Stress-corrosion cracking is a cracking process that requires the simultaneous action of a corrosion mechanism and sustained tensile stress.

wastage is the dominant mode of failure in the model calculations. This approach leads to typical projected times-to-failure on the order of tens to hundreds of thousands of years for the inner wall.

The number of patches in contact with water is a major source of uncertainty. Uncertainty in the values of uniform corrosion rates is being addressed by continuing long-term laboratory corrosion tests (Stahl 1997). Uncertainty in the conditions leading to the onset of localized corrosion also is being addressed in laboratory tests at Lawrence Livermore National Laboratory (LLNL), the University of Virginia, the Center for Nuclear Waste Regulatory Analyses, and the corrosion research community at large. This research is very important for reducing uncertainty in known modes of deterioration.

Galvanic protection[14] of the high-nickel alloy of the inner wall by the less noble (less corrosion-resistant) carbon steel of the outer wall once was thought to be an important contributor to performance. However, in part because of the opinions of experts on the Waste Package Degradation Expert Elicitation Panel, galvanic protection is not part of the TSPA-VA base case, although some experimental work on galvanic protection continues. If the results of this work are favorable, limited galvanic protection again could become part of the base case.

c. Issues

Recent performance assessments and the draft license application plan recently prepared by the DOE clearly indicate that the EBS is a very important link in determining the performance of the overall repository system for the first 10,000 years and longer of the repository's life. The waste package is the most critical component of the EBS.

Current and alternative waste package designs take into consideration expected corrosion mechanisms and service factors leading to the conditions where those mechanisms are present. Design teams and experts have covered many scenarios (Whipple et al. 1998, WPDEE 1998). Issues are still open involving use of available information or information from ongoing experiments. They include determining the possibility of mechanical deterioration of the inner wall by "denting" (from accumulation of corrosion products between the outer wall and the inner wall), determining in short experiments the minimum temperature for development of crevice corrosion, assessing the susceptibility of titanium alloys to hydrogen embrittlement under repository service conditions, determining the corrosion effect of sulfur-bearing aqueous species, and establishing the potential advantages of heat treating the waste package after the closure weld is completed. These issues have a good chance of being resolved in the short term.

Fundamental investigations to date have not revealed a mechanism whereby fast corrosion rates could develop in the materials considered (Alloy 22, titanium alloys), even if a moderately aggressive environment were to be maintained at the immediate metal surface. However, those materials are relatively new and have been investigated for only a limited time (decades) under any conditions and for only a few years under conditions that directly apply to the expected waste package environment in Yucca Mountain. Unlike the case of some iron or copper alloys that have been used for thousands of years, there is little or no comparable experience with alloys of metals that rely on passivity for corrosion protection.

This is a critical issue because the history of corrosion has sobering examples of unexpected modes of failure of materials that had otherwise good service prognoses (Dillon 1998). Central to this issue is understanding how stable metal passivity can be over the extremely long repository time scale. Answering that question may require reexamining the present theoretical base on metal passivity (Macdonald 1992). Other subtle effects on corrosion performance that may fail to show up in short-term experiments but that could prove critical in millennial time frames may include slow phase transitions, effects

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[14] Galvanic protection is protecting a metal from corrosion in the presence of an electrolyte (such as water containing dissolved salts) by providing physical contact with a more electropositive metal, which will corrode first.

of ionizing radiation on corrosion properties, and low-dose radiolytic phenomena.

Waste package performance depends not only on the base of knowledge of materials performance, but also on how that base of knowledge is applied. In particular, quality control in manufacturing is critical. In the present TSPA-VA formulation, juvenile failures resulting almost entirely from manufacturing or handling errors are the single dominant source of exposure to the public during the early repository service life. This underscores the importance of advancing a credible and implementable plan for quality control in manufacturing.

Because of the importance of waste package performance, a major limit on any efforts to project the corrosion behavior of the packages must be understood. That limit is the assumption that no unknown mechanisms will affect the integrity of the packages over the long time of interest. This assumption, usually implicit, is crucial to the value of any service-life projection.

3. *Zircaloy Cladding*

Currently, the DOE plans to take performance credit for zircaloy cladding in the base case of TSPA-VA. Data on general corrosion of zircaloy cladding are extensive (Franklin 1997, Hillner et al. 1998). Most of the data are on conditions within nuclear reactors that arguably are significantly different from the modified environmental conditions that Yucca Mountain would impose on zircaloy cladding. If zircaloy cladding is exposed to environments that are strongly acidic and severely oxidizing, pitting corrosion is possible. Although such an environment *outside* the waste package is unlikely, the possibility of its occurrence *inside* some emplaced waste packages has not been ruled out.

What needs to be determined is whether the combined interactions of corrosion products from the inner and outer walls, radiolysis, water, and elevated temperatures could produce a corrosive environment inside waste packages. Both theoretical work (e.g., using computer programs that model thermodynamic equilibrium) and experimental (laboratory) work are needed to predict the ranges of local environmental conditions that could exist inside a waste package and the probabilities of their occurrence. The importance of the work to the performance of the zircaloy cladding is an additional reason that the experimentation and modeling discussed earlier in this paper should be done to determine the environments of materials inside the waste package.

Zircaloy cladding may be an exception to the general rule that barriers fail sequentially from the outside. Corrosion caused by pellet-cladding interaction (PCI)—stress-corrosion cracking from the inside of the cladding caused by the interaction of spent-fuel pellets and the cladding—has been studied, but is not fully understood. In addition, about 1 percent of commercial spent fuel is clad in stainless steel, and about 1 of every 1,000 zircaloy-clad spent-fuel rods may arrive at the underground facility showing cladding penetration (Siegmann 1997). According to the DOE, intact fuel rods would not fail (defined as the first pinhole penetration) by general corrosion until many thousands of years after water first contacts them (McNeish 1998b). However, rockfalls or other mechanical forces may cause rod failure as soon as the inner and outer walls of the waste package corrode to the point where they no longer protect the rods.

Except for PCI, sufficient data exist to predict the *general* corrosion behavior of cladding in the underground facility. Predicting the contribution of zircaloy cladding to long-term performance may be difficult, however, because (1) a small fraction of the cladding already would have failed during nuclear power plant operation; (2) few data exist for estimating the damage (if any) to cladding during storage (particularly dry storage), handling, and transportation and the effects of such damage on performance; (3) little study has been done of the potential for cladding damage in an intact container (e.g., by radiolysis of water or air inadvertently trapped in the waste package during loading); (4) the potential for hydride embrittlement of irradiated zircaloy cladding has not been addressed fully; (5) limited study has been done of the degradation of cladding after a waste package is breached; and (6) essentially no data exist on the extent of *localized* corrosion of zircaloy under Yucca Mountain conditions.

4. Spent-Fuel Pellets

When water reaches the spent-fuel pellets, the fission products and actinides in the pellets begin to dissolve. The amount of each fission product and actinide that can dissolve in a unit quantity of water depends on the solubility of each material, which is influenced by the specific chemical composition of the water. Thus, it is important to know the conditions that would evolve on and inside waste packages as a result of interactions between waste package materials and corrosion reactions, corrosion products, radiolysis, and external environmental conditions.

The solubilities of many fission products and actinide species are known reasonably well in a variety of environments. Despite several studies,[15] however, a high degree of uncertainty remains about the solubilities of various forms of neptunium, a constituent of spent fuel that appears to be the most important contributor to doses far into the future. The solubility of neptunium is discussed in the UZ chapter of this report.

C. Waste Package Enhancements

Currently, the DOE, through its M&O contractor, is studying enhancements to the current design of the waste package. Two often-mentioned enhancements under study are *drip shields* and *ceramic coatings.*

1. Drip Shields

A drip shield is anything placed on or over a waste package to protect the package from dripping water. An example of a drip shield is a thin (e.g., 5 mm) semicircular sheet of metal (e.g., a titanium alloy) completely covering, conforming to, and resting on the waste package. Another example is a thicker self-supporting semicircular metallic sheet that sits slightly above a waste package rather than resting on it.

Design issues associated with drip shields include how to protect a drip shield from rockfalls and how to ensure that the drip shield remains in place. Placing backfill over a drip shield to cushion it from rockfalls and prevent it from moving is one of the ideas advanced by the M&O. If backfill that provides a high degree of capillary action (e.g., a Richard’s barrier) were used, it could replace the drip shield completely, at least for low drip rates.

Issues concerning drip-shield materials are largely the same as issues concerning the waste package inner and outer walls and the zircaloy cladding—that is, the validity of models for predicting drip shield corrosion rates and the adequacy of the data on which the models are based. If the drip shield material is the same as the inner-barrier material (Alloy 22), then models and data used to predict inner-barrier lifetime would be equally useful for predicting drip shield lifetime. If the drip shield uses a different material, the adequacy of models and data for predicting its lifetime would need to be addressed on a case-by-case basis.

2. Ceramic Coatings

Conceivably, a thin coating of ceramic material could protect the waste package. This subject requires much research, however, to determine whether long-lasting ceramic coatings can be manufactured without flaws (e.g., cracks) and whether ceramic coatings are sufficiently resistant to handling and thermal stresses.

D. Alternative Waste Package Designs

In contrast to waste package enhancements, which are features added to the existing design to supplement its performance, alternative waste package designs are major revisions of the current design or its replacement by new concepts. In the Board’s most recent summary reports to Congress and the Secretary of Energy, the Board urged the DOE to examine alternative designs (NWTRB 1997 and 1998a). Examples of alternative waste package designs include (1) a waste package with inner and outer walls of two corrosion-resistant materials (e.g., a titanium alloy and Alloy 22), rather than the current design that

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[15] The studies have been summarized by Sassani and Siegmann (1998).

uses an outer wall of a corrosion-allowance material (carbon steel) and an inner wall of a corrosion-resistant material (Alloy 22) and (2) reversal of the order of the inner and outer barriers (an outer barrier of Alloy 22 and an inner barrier of carbon steel). These and other alternative waste package designs were discussed at the recent workshop conducted by the Board's Panel on the Repository (NWTRB 1998b).

Although analysis of alternative waste package designs to date has been very limited, alternatives using Alloy 22 or titanium alloys as the *outer* wall appear to obviate one significant uncertainty of the current design: whether the modified environmental conditions (i.e., potentially high ferric chloride concentrations and low pH) that *might* result from interaction of the current design's steel outer wall and the external environment would be corrosive to the nickel-alloy inner wall.

E. Other Waste Package Issues

1. Juvenile Failures

Juvenile failures of waste packages are premature failures. That is, they are failures that occur before a waste package would be expected to fail in an underground facility because of corrosion or other degradation processes. Juvenile failures do not include failures that are due to disruptive events (e.g., volcanism, human intrusion). The following examples are some potential causes of juvenile failures:

- A waste package is fabricated from materials containing a significant flaw (e.g., a large void in the metal plate used to fabricate the package), and the flaw is not detected during the inspections before emplacement or during the performance confirmation period.

- The final closure weld of a waste package is done incorrectly, creating a flaw, and the flaw is not detected in subsequent inspections.

- A waste package is mishandled (e.g., dropped) during emplacement in a way that seriously damages it, and the drop is not reported.

The DOE recognizes the potential for juvenile failures and has studied the issue. The TSPA-VA base case includes juvenile failures (McNeish 1998a).

2. Manufacturing, Waste Package Closure (Welding), and Nondestructive Examination

Manufacturing a waste package, making final closure welds on it, and performing nondestructive examination of the package and its welds are well within the general state of the art. Nevertheless, significant specific development work remains, and prototype waste packages need to be constructed to perfect manufacturing, welding, and examination procedures and equipment. To date, the DOE has advocated a construction method involving shrinkfitting the inner and outer walls of the waste package. Shrinkfitting[16] is easy to do, but it introduces many uncertainties—particularly about the effects of residual stresses from the shrinkfitting operation and about procedures for final closure welding. Loose-fit construction could eliminate the uncertainties involved in shrinkfitting without introducing significant new uncertainties.

3. Long-Term Research and Monitoring

The present state of knowledge suggests, but does not prove, the capability of the waste package to contain spent fuel for hundreds of thousands of years. Continuing materials research and monitoring is vital for at least several decades into the period of underground facility operations, and probably until underground facility closure. The research would include monitoring of emplaced waste packages, placement of corrosion-test samples in and around emplaced packages, laboratory experiments, and analyses. There are at least three important reasons for this research:

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[16] Shrinkfitting is joining (or mating) layers of metal by using heat to expand an outer shell, inserting an inner shell, and allowing the outer shell to cool around the inner shell.

- Confirmation of long-term predictions (e.g., corrosion rates, phase stability) that were based on short-term data.

- Reduction of the possibility that unknown mechanisms or defects exist that could compromise performance (in particular, the nature and long-term stability of protective films).

- Investigation of innovative packaging techniques or materials offering cost saving or improved performance.

4. Criticality

The probability and consequences of postclosure criticality[17] have been analyzed extensively by the DOE, particularly in the last 2 years. For commercial spent fuel, the analyses indicate that criticality incidents are unlikely and that the occurrence of criticality would have minor consequences. Some wastes, particularly highly enriched spent fuel (e.g., from some research reactors), can be more difficult than commercial spent fuel to analyze for criticality.

VI. Conclusions

The engineered barrier system, that is, the underground facility and waste packages working together, performs a vital role in the operational and postclosure performance of the geologic repository. The Board's conclusions about EBS issues are summarized below.

- Evaluations of alternative concepts for underground facility design are needed, especially of concepts that may provide the same level of performance but with less uncertainty than provided by the current underground facility design. For example, a ventilated repository design with lower peak temperatures could reduce current uncertainties about the heat-induced hydrologic, mechanical, and chemical changes in the rock surrounding tunnels and could reduce the rates of waste package corrosion and radionuclide mobilization from the waste.

- Predicting the performance of a waste package design is a matter of predicting the external (tunnel) environment of the waste package, how the waste package and its environment would interact to modify the environment, and how the materials used in the waste package would degrade (corrode) in response to the environment. High confidence in performance predictions for the nickel-alloy inner wall of the current design is needed because of its importance to waste package longevity. Research could determine if the present package design could easily generate, beneath the remains of the carbon-steel outer wall, an environment aggressive enough to deteriorate the corrosion-resistant alloy quickly. Research also is needed to confirm long-term predictions (e.g., corrosion rates, phase stability over tens of thousands of years). These predictions are based on knowledge gained during only the past several decades for materials that rely on passive films for corrosion protection and on data gained during only the past year or so for Alloy 22 under Yucca Mountain conditions.

- Several alternative waste package concepts include outer walls of high-performance materials, such as titanium alloys or Alloy 22. These alternatives offer the promise of lasting tens of thousands of years or longer, given the range of environmental conditions and the spatial and temporal distribution of dripping that may be found within the underground facility. Adoption of one of these concepts could substantially reduce part of the uncertainty associated with the current waste package design. Research still would be needed, however, to confirm the viability of the alternatives.

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[17] "Criticality" means the development of a self-sustaining nuclear fission reaction.