WASTE PACKAGE FOR YUCCA MOUNTAIN REPOSITORY: STRATEGY FOR REGULATORY COMPLIANCE

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ABSTRACT

This document summarizes the strategy given in the Site Characterization Plan (SCP) (1) for demonstrating compliance with the post closure performance objectives for the waste package and the Engineered Barrier System (EBS) contained in the Code of Federal Regulations, Title 10, Part 60 (10 CFR60), (2) particularly 10 CFR 60.1113, and other applicable documents. The strategy consists of the development of a conservative waste package design that will meet the regulatory requirements with sufficient margin for uncertainty using a multi-barrier approach that takes advantage of the unsaturated nature of the Yucca Mountain site. This strategy involves an iterative process designed to achieve compliance with the requirements for substantially complete containment and EBS release. The strategy will be implemented in such a manner that sufficient evidence will be provided for presentation to the Nuclear Regulatory Commission (NRC) so that it may make a finding that there is "reasonable assurance" that these performance requirements will indeed be met. In implementing the strategy, DOE recognizes four fundamental goals: (1) protect public health and safety; (2) minimize financial and other resource commitments; (3) comply with applicable laws and regulations; and (4) maintain an aggressive schedule. The strategy is intended to be a reasonable balance of these competing goals.

INTRODUCTION

As shown in Fig. 1, the focal point of the strategy is the waste package design. The waste package includes the waste form, any containers, and any materials within or immediately surrounding a container. The strategy considers all of these components in developing the wastepackage design. Fig. 1 depicts two stages involved in the implementation of the waste package strategy; a design development stage followed by a design characterization and evaluation stage. Inputs to the waste package design include repository design and scenario information. The scenarios are based on waste form and site data and the interpretation of important regulatory terms which are not defined in the regulatory documents. These inputs and regulatory requirements form the overall design bases from which a design can be developed. These design bases are continually evaluated as information becomes available and additional scenarios are developed and may be revised prior to the start of a new design phase.

The design characterization and evaluation stage begins after development of a design concept and includes testing, modeling, performance allocation, and performance analysis. The results of this stage determines technical adequacy of cost effectiveness of the proposed concept. Adjustments of models and performance allocations can be made during this stage to determine the adequacy of the proposed design. If the design is not adequate, the strategy directs a return to the design development stage for development of a new design and/or revised interpretation of regulatory terms and design bases.

DOE had developed a conceptual waste package design which provides the basis for the plans defined in the SCP and, as such, is DOE's current reference design (1). This design is based on currently available data and interpretations and employs a container as the primary barrier for the containment period and the waste form as the primary barrier for radionuclide release control following the containment period. The reference design assumes that the package will be emplaced in a vertical borehole in a manner that will maintain an air gap that impedes the transfer of water from the rock to the container or waste form.

A candidate metal containment barrier will be selected and characterized, based on a parallel experimental and performance modeling effort. Alternative barrier design concepts and materials will be developed in parallel with the metal barrier design effort to satisfy regulatory requirements for alternative designs and to provide a backup to the metal barrier design should it fail to meet its performance requirements.

Top-level performance goals have been defined for both containment and controlled release to assign performance to each component of the waste package system, including the containers and the waste form, for both the spent fuel (including the cladding) and the high-level waste (HLW) glass. Performance assessment modeling will be used to test whether the performance goals have been met. If not, then changes are made in an iterative manner to the performance allocation process, waste package design or materials, modeling, experimental data, or regulatory interpretation, until the performance requirements have been met.

This document is intended to provide an overview of the waste package strategy. The current reference waste package design and the tentative performance goals are used in the discussion for explanatory purposes and may not reflect the final design of the waste package or the final performance goals to be established through testing and modeling. The following sections will discuss each element of the strategy as outlined on Fig. 1. The next four sections discuss the design development elements of the strategy and

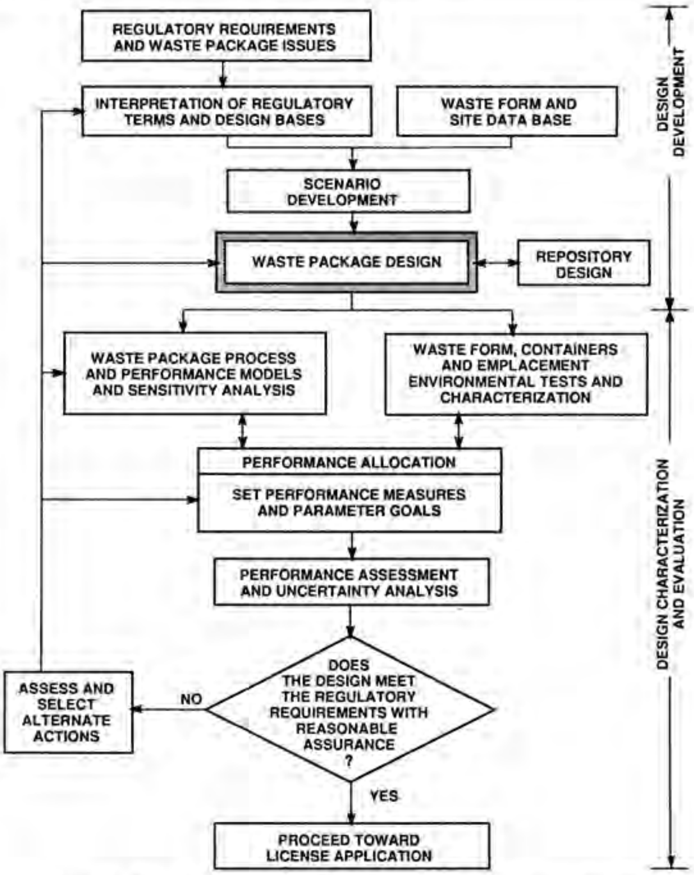

Fig. 1. Waste Package Postclosure Compliance Strategy.

the following three sections present the design characterization and evaluation elements.

REGULATORY REQUIREMENTS AND INTERPRETATION OF REGULATORY TERMS

Regulatory Requirements

Assuming anticipated processes and events, the two post-closure objectives for the EBS in 10 CFR 60.113 require (1) "substantially complete containment" within the waste packages for up to 1000 years (the containment period) and (2), following the containment period, control of the release of any radionuclide from the EBS to less than 1 part in 100,000 per year (the controlled release period). Although the containment period may stretch for 300 to 1000 years after closure as per 10 CFR 60.113, 1000 years is issued for design purposes. By reference to 40 CFR 191, the release-control period continues until 10,000 years after closure of the repository (3). These post-closure performance requirements are without precedence for engineered systems. This presents a unique engineering challenge that goes beyond the usual considerations of classical reliability engineering. These considerations are the focus of much of the document, and lead to the arguments that are being developed for demonstrating compliance.

Other regulatory requirements in addition to 10 CFR 60.113 affect the waste package design, including requirements for retrievability, criticality control, consideration of alternative designs, a performance confirmation program, and specific waste package design criteria. In addition, the waste package must support the repository and geologic systems in meeting requirements in 10 CFR 20, 10 CFR 960, and 40 CFR 191 (4,5,3). Certain aspects of waste package design are definitely driven by these requirements, but there are no identified cases of incompatibility. The most stringent requirements on the waste packages are the post-closure performance objectives of 10 CFR 60.113.

Interpretation of Regulatory Terms

The NRC requirements do not quantitatively define what is meant by "anticipated processes and events," substantially complete containment," and the "EBS boundary." An interpretation of these terms was made by the Department of Energy (DOE) to develop the compliance strategy. "Anticipated processes and events" are interpreted to have a probability of occurring equal to or greater than 0.1 during the period when the intended performance objective must be achieved. The interpretation of "substantially complete containment" can be summarized with the following statements: "Containment will be based on the ability of the waste package, by virtue of its intrinsic properties and design, to maintain a continuous, sealed barrier around the waste...The DOE will design the waste packages to provide total containment of the enclosed waste for the containment period under the full range of anticipated repository conditions" (1). Lastly, the DOE has tentatively interpreted the boundary of the EBS to coincide with the surfaces of the excavations within the underground facility, specifically the waste-package emplacement borehole wall. A reassessment to include a portion of the host rock within the EBS is reserved for a later design phase.

Containment Performance Goals

Consistent with the above qualitative interpretation, DOE has derived two top-level performance goals for containment. Containment of the waste within the set of waste packages will be considered to be substantially complete for up to 1000 years after repository closure, as long as:

1. For each of those radionuclides of regulatory significance to long-term isolation (i.e., those whose release is limited by 10 CFR 60.113(a)(1)(ii)(B)), its release rate from the set of emplaced waste packages during the containment period does not exceed 1 part in 1 million per year of its inventory calculated to be present at 1000 years following repository closure, and
2. For each of those radionuclides whose release is not limited by (1) above, its release from the set of emplaced waste packages during any year of the containment period does not exceed 1 part in 100,000 of the total inventory of that radionuclide calculated to be present in the waste in that year.

For the radionuclides of regulatory concern, the release rate performance goals were set an order of magnitude more stringent than those for the same isotopes during the post-containment period. The performance goals for the release of the other (short half-life) radionuclides were set so that they introduce no credible postclosure risk to present and future generations.

WASTE FORM AND SITE INFORMATION

A definition of the waste form characteristics and waste package environment must be known or assumed prior to selection of a design concept. Currently available data were used to develop the reference design. These data will be reviewed prior to start of the Advanced Conceptual Design (ACD) phase and the waste package environment and the waste form characteristics will be redefined as appropriate. The following sections summarize the currently available database.

Waste Form Data

The two basic waste forms expected at the repository include spent fuel from commercial light-water reactors and borosilicate glass containing high-level waste from reprocessing. Of these, spent fuel will dominate, both in radioactivity and in volume. Under the present design and operating assumptions, about 30,000 spent-fuel waste packages will be emplaced, along with about 13,000 packages of HLW in borosilicate glass. The character and behavior of the HLW glass is fairly well understood. However, much needs to be known regarding the behavior of spent fuels, particularly those from the more current extended-burnup fuels.

Because both consolidated and intact assemblies of both Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) fuel may need to be accommodated in the waste packages, the internal configuration must be flexible, yet allow for a limited number of external dimensions to

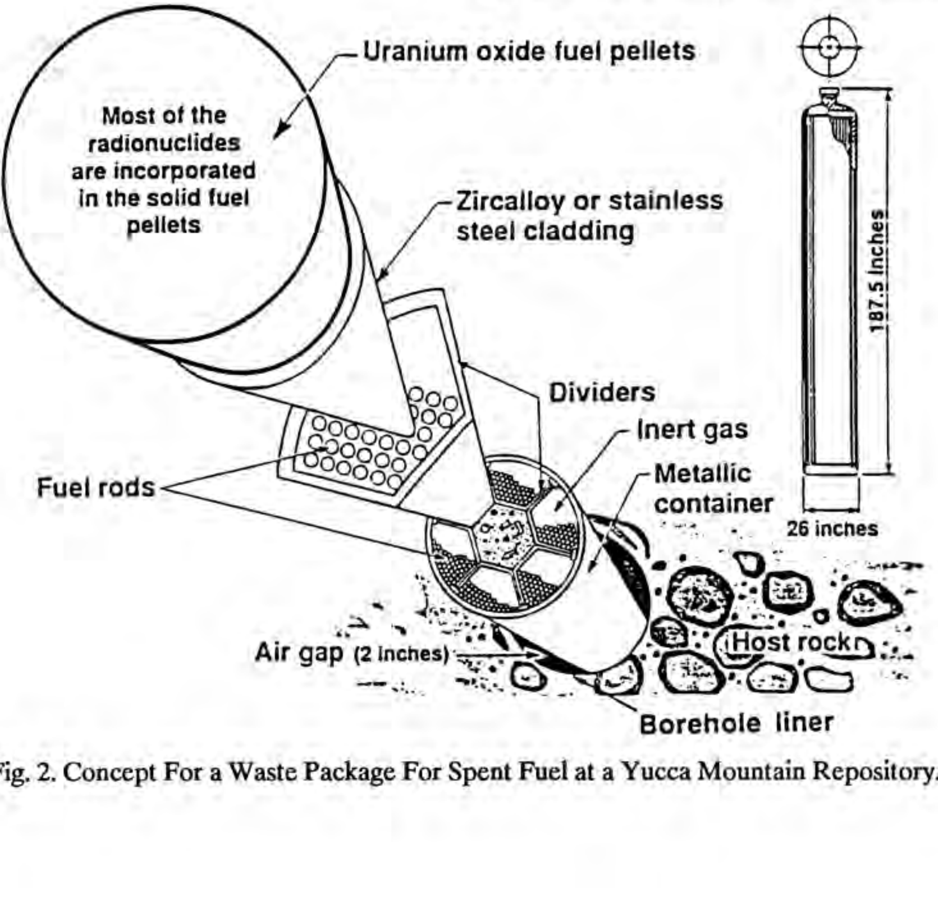

Fig. 2. Concept For a Waste Package For Spent Fuel at a Yucca Mountain Repository.

simplify repository packaging and handling equipment. Fig. 2 shows a sketch of a spent fuel waste package for consolidated fuel. Minor amounts of other miscellaneous HLW may also be emplaced. In addition, the NRC has recently published a notice of proposed rulemaking that would require emplacement of "greater than class C" wastes in the repository (6). No specific waste package designs have been developed to accommodate such waste, although the impacts on the repository system are potentially severe. Such wastes could require up to 10,000 additional waste packages.

Site Data

The existing site information has been used to develop the waste package environment scenario. This information is a product of past site characterization activities that have been limited to selected drillholes. Planned site characterization activities defined in the SCP will reduce the uncertainty as information becomes available.

WASTE PACKAGE ENVIRONMENT SCENARIO

The design bases for the reference design include expected and bounding scenarios developed from currently available site data. The expected scenario is based on the expected conditions at Yucca Mountain, namely an unsaturated, fractured, slightly porous rock (densely welded tuff) with a low water flux downward through the repository horizon. A schematic cross section of the Yucca Mountain repository is shown in Fig. 3. The undisturbed groundwater is expected to resemble water taken from a nearby well, J-13. Following emplacement, the heat from the waste will gradually increase the surrounding rock temperature, peaking in about 20 years to about 230 C at the borehole surfaces next to the hottest packages. Most of the packages will remain above the boiling point of the water (97 C) for 300 years. Thus, the environment within the boreholes is expected primarily to be hot, humid air with no liquid water contacting the waste packages. Although not expected to be a significant factor, radiolysis of the water vapor-air mixture at the container surface is a potential source of species that could cause or enhance container material corrosion.

As the rock temperature increases, capillary water will vaporize and migrate through the rock pores and fractures. Some water will be carried away in the repository ventilation system, but most will condense in cooler rock, away from the waste packages. The fate and composition of this water is the subject of ongoing studies; much of it could be removed from the repository level by drainage along fractures. After the rock cools below the water's boiling point, water is not expected to flow into the borehole from the unsaturated porous matrix. However, flow from isolated fractures cannot be ruled out.

The bounding scenario defines a range of water composition and quantitiy that must be tolerated by the referenced design. the volume of water potentially contacting

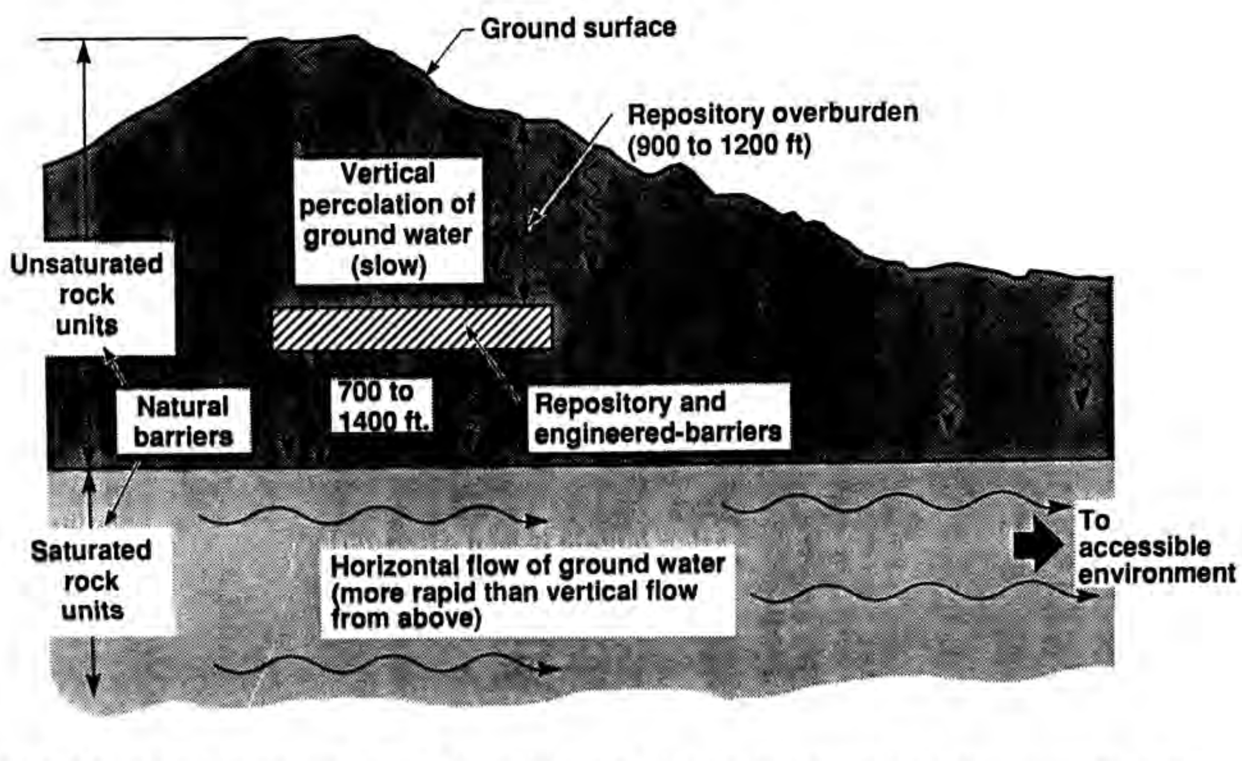

Fig. 3. Schematic Cross Section Through Yucca Mountain, Showing the Saturated and Unsaturated Rock, the Repository Including the Engineered Barrier System, and the Principal Paths of Water Flow.

some of the waste packages during the containment period is based on a conservative upper bound of current percolation rate through the repository horizon. At the 0.5 mm-per-year flux, 0.25 L per year and 1.9 L per year are approximately the respective quantities of water that pass vertically through vertical and horizontal waste emplacement boreholes. Applying a factor of conservatism yields the value of 5 L per year per package. The volume of water potentially contacting some of the waste forms during the post-containment (controlled release) period assumes a larger factor of conservatism; i.e., 20 L per year per waste package. The design goal for the number of packages contacted by liquid water is 5% for the first 300 years and 10% thereafter.

The current design bases for either the reference or alternative design do not include the potentiality of total saturation at the repository horizon, and resultant immersion of all the waste packages in groundwater. However, the parallel development of alternative waste package designs provides leeway for additional uncertainty in water chemistry and quantity beyond the bounding scenario described in this section.

REFERENCE AND ALTERNATIVE WASTE PACKAGE DESIGNS

The reference design provides for a cylindrical container that is about 66 to 71 cm (26 to 28 in.) in diameter with a 1 to 3 cm (3/8 to 1-3/16 in.) wall thickness. the overall length is either 328 cm (10.5 ft.) or 476 cm (15.6 ft.) to accommodate the HLW glass or spent fuel, respectively. All container material for the reference design will be selected prior to Advanced Conceptual Design (ACD) from among the six current candidates, which include austenitic alloys (Type 304L and Type 316L stainless steel and Alloy 825) and copper alloys (Pure copper, aluminum bronze, and copper-nickel). These candidates are in separate alloy families that have different failure modes in the expected environment. At present, the Alloy 825 and the 70 copper-30 nickel alloy appear to be the most promising candidates.

Simultaneously, alternative waste package designs will be selected from among concepts that are inherently more conservative that the reference design and avoid similar failure modes. These concepts include materials such as ceramics, bimetallics, coatings, and fillers.

Because of the level of uncertainty in site data, both the reference and alternative waste package designs will be carried through the ACD phase. Model development will parallel the experimental effort to assure that the behavior of the material selected for the reference or alternative design can be adequately modeled. Contingent upon sufficient reduction of uncertainties in the waste package environment scenario, a single concept will be selected for the License Application Design (LAD) phase.

MODELING, TESTING, AND PERFORMANCE ALLOCATION

Given a reference design, the strategy moves from design development to design characterization and evaluation. This first involves an iterative process of modeling, testing, and performance allocation. To initiate the process, performance goals have been tentatively allocated, based on existing data and professional judgement, to components of the waste package during the containment and controlled release periods. These allocations will be periodically adjusted as data and insights on the performance of the barriers becomes available. For the containment and controlled-release periods, both an expected scenario, in which the repository remains unsaturated and no liquid water contacts the containers, and a bounding scenario, in which a limited amount of water can contact the containers, are analyzed.

Containment Period

In order to allocate performance to engineered subsystems and components and carry out analyses for assessing performance, two quantitative release rate goals were established for the containment period as discussed in the second section. The performance allocation strategy recognizes three time segments within the containment period - the first 100 years post closure, 100 to 300 years, and 300 to 1000 years - to reflect the changing radionuclide characteristics, both in decay heat and the inventory of specific radionuclides. In the first 100 years, the inventory is dominated by the short half-life radionuclides. Later, the inventory is dominated by the actinides with increasing concern for a few soluble long-lived radionuclides.

Given the quantitative top-level release rate goals and the three time segments, performance is allocated to the components of the waste package. All of the potential components of the waste package are listed in Table I. However, credit is currently taken for only a portion of them. The product of the allocations for the fractions of failed containers, failed cladding, water-contacted containers, and inventory releasable from the waste forms must yield a value not exceeding the release limits given above. The initial allocation of performance in the SCP and tentative performance goals are different for the spent fuel waste packages than for the HLW glass waste packages, primarily because the two waste forms differ greatly in their physical, chemical, and nuclear characteristics. However, each set of waste packages will be shown to be in compliance independent of the other waste form. The tentative goals are established on the basis of available technical information, generated by the program or obtained from the literature, and professional judgement in the absence of sufficient information to estimate their achievability accurately. In some cases, the performance goals are back-calculated from the release requirements. However, implicit in this process is a mechanism for periodic review and adjustment of the goals as additional data or insight into performance becomes available.

Allocations were made for each component of the reference waste package for two scenarios: the expected scenario in which essentially no water contacts the containers; and the bounding scenario in which some containers could be exposed to a small amount of water. For the expected scenario, the loss of containment and subsequent release of radionuclides will be limited to vapor-phase processes. The primary mechanism for failure of the

TABLE I
Elements and Functions of the Engineered Barrier System and the Identification of Elements to Which Performance is Currently Allocated.*

Element	Function	Allocation
Barae fuel or glass waste	Provide very low dissolution rate in water	Yes
Fuel cladding	Prevent access of water to fuel	Yes
Glass pour canister	Prevent access of water to glass waste	No
Solid filler within container	Change chemical environment near waste; prevent access of water to waste	No
Container	Prevent access of water to waste.	Yes
Packing Material	Retard radionuclide release	No
Borehole liner	a. Maintain retrievability,b. control rock or water contact with container	Yes No
Adjacent rock	Retard radionuclide release	No

* Other elements which are present but for which no performance allocation is required include: inert gas in containers, air gap between the containers and rock, spacers between the container and the borehole wall, and the engineered thermal field in the repository.

container would be oxidation in an air-water vapor environment. Containers could also fail as a result of emplacement or in-service mechanical stresses. Reasonable goals were assigned to the container failure rates, which are consistent with failure rates found for nuclear steam drums and pressure vessels.

The bounding scenario assumes that 5 L per year per packages of liquid water contacts the containers of 5 percent of the waste packages for the first 300 years post-closure and 10% thereafter. No liquid water contacts the containers in the remaining waste packages. This assumption is based on the unsaturated nature of the site. The possible modes of container failure in the founding scenario include oxidation failure in the absence of water and localized corrosion, primarily stress corrosion cracking, in the presence of water. Reasonable goals were established for the container failure rates that are higher than those used for the expected scenario, which is consistent with the expected higher failure rates due to aqueous corrosion. For the bounding scenario, the principal concern is the release of the long-lived soluble species, Tc-99, Cs-135, and possibly I-129.

Post-Containment (Controlled Release) Period

The quantitative release rate goals for the post-containment period are identical to those in 10 CFR 60.113, namely that the release rates for any radionuclide of regulatory concern not exceed 1 part in 100,000 of the 1000 year inventory of that radionuclide per year. For release control, the time period extends to 10,000 years post-closure and the waste form is the primary barrier to release. Performance is allocated to each component of the waste form, as noted above. Two functions are assigned to the container: (1) the breach rate is spread in time to limit the release of highly soluble, rapidly released gap and grain boundary radionuclides; and (2), the container wall surface and geometric shape is maintained in order to hold the waste separated from the water in the rock or allow only a small amount of water to be in effective contact with the waste and provide mass transfer resistance to release. Performance is allocated to each of these functions. the product of the container and waste form allocations must yield a value not exceeding the above release rate limits.

As above, for the expected scenario, only vapor-phase releases are possible. This is limited to C-14 during the post-containment period, in the case of spent fuel. However, for HLW glass, no radionuclide species exist in the vapor state at the conditions in the repository, except for radon gas which is building up from the decay of Ra-226. However, the longest-lived isotope has a half life of 3.82 days (Rn-222), which precludes its release to the accessible environment. The bounding scenario assumes that 20L per year per package of liquid water contacts the waste forms in 10 percent of the waste packages during the controlled release period. This assumption is based on the unsaturated nature of the site. In the post-containment period, the principal radionuclides of regulatory concern are Tc-99, Cs-135, and possibly I-129. Of these Tc-99 has the largest radioactive inventory. It should be noted that these aqueous releases include both dissolved and suspended material (colloids, particulates, etc.).

PERFORMANCE ASSESSMENT AND ALTERNATE ACTIONS

Performance assessment is a process used to determine whether the waste package design meets the regulatory requirements. The results of modeling experimental data to predict barrier performance, including uncertainty, under a range of repository conditions is compared with the allocations tentatively assigned. For the Yucca Mountain project, the performance assessment code utilized is PANDORA (7). It is composed of seven coupled process modules: radiation, thermal, mechanical, environmental (water flow), corrosion, waste form alteration, and radionuclide transport. These process modules are summaries of process codes, which are detailed simulations of physical or chemical processes based on fundamental understanding of the process mechanism. The code will look at both deterministic and probabilistic variations among waste packages, and sum the result over all waste packages.

If the design meets the requirements, then license application activities can proceed. If the design does not meet the requirements, then the evaluation and selection of alternative actions is performed. These include assigning performance goals to additional components, performance of additional tests to improve data bases for the waste package or environment, changes in waste package design or materials, or modification of the computational models. The process iterates, as shown in Fig. 1, until the design meets the requirements.

TECHNICAL UNCERTAINTIES AND POTENTIAL RESOLUTION

The major technical uncertainties or adverse results that could impact the implementation of the postclosure strategy include the following:

1. For the reference container: (a) Late confirmation (post-1992) that the repository environment is close to expected, and well within, the bounding conditions; and (b) The inability to achieve laboratory confirmation of actual mechanisms of degradation modes to provide "reasonable assurance" of containment performance.
2. For the alternative container: The inability to demonstrate production or remote closure technology for full-size prototypes prior to start of LAD.
3. For the spent fuel waste forms: The inability to confi.rm, prior to license application the expected unsaturated environment, thus requiring the evaluation of other uncertainties: (a) principal of these is the demonstration that sufficient mechanistic understanding exists for the release of radionuclides from spent fuel, including extended burnup fuel which is not yet available, but which will form the major portion of the inventory at the time of emplacement; (b) demonstration of solubility-limited release for most of the radionuclide species is also absolutely essential; and (c) release by other mechanisms such as colloidal transport and biological effects must also be understood.

Because the reference and alternative container designs have independent uncertainties, carrying both through at least ACD is the mitigating strategy. For example, the use of a bimetallic container with inner and outer liners from different alloy families, chosen to reflect the changing environment of temperature and irradiation field, should preclude the failure of both liners. A still more robust container could include a ceramic or graphitic container with a metallic overpack. Another option is the use of an internal filler. These alternatives are more complex and costly than the reference design. However, they should provide greater assurance that the containment and release requirements will be met.

The decision on whether to utilize the reference design or the alternative design as the basis for the license application design will hinge on the availability of the information on the characteristics and behavior of each barrier material and adequate knowledge of the environmental design envelope. The material and design chosen must successfully pass through the strategy outlined in Fig. 1. If more than one passes through, the choice would be based on other considerations. If none of these meet the requirements, other options would have to be explored, including revision of the regulatory design bases as provided in 10 CFR 60.113(b).

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