Waste Package Development Technical Document (WPDTD)

Revision 01

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May 29, 1996

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1.0 INTRODUCTION

The basis for the development of the Waste Package (WP) Subsystem and Engineered Barrier (EB) Segment design involves many elements. These elements include the requirements, design goals, environmental scenarios, interfaces with other engineered features and the natural barriers, engineered barrier system performance, and programmatic inputs. These are detailed in the following sections however, the major requirements for design are stated in the current revision of the *Engineered Barrier Design Requirements Document* (EBDRD), (YMP, 1994).

1.1 Objective

The Waste Package Development and Waste Package Materials organizations are tasked with the design and development of the Waste Package Subsystem and the evaluation, testing and modeling of EB Segment materials directly affecting waste isolation capability. In addition, the Waste Package Development and Waste Package Materials organizations will provide design input for the Underground Facility Subsystem. Repository Design is the lead organization for the design of the Underground Facility Subsystem. The Waste Package Development and Waste Package Materials organizations contribute directly to the goal of creating an Engineered Barrier Segment that can meet regulatory-based requirements in a way that compliance with the regulations can be demonstrated in a repository licensing proceeding before the Nuclear Regulatory Commission (NRC).

The source of requirements for the EBDRD is the Mined Geological Disposal System Requirements Document (MGDS-RD). The MGDS-RD is one of four System Requirements Documents (SRDs) that obtain requirements directly from the CRWMS Requirements Document (CRD). The CRD is the ultimate source of requirements used in the Design Requirements Documents (DRDs) and SRDs. The CRD obtains its requirements from the Code of Federal Regulations (CFRs), Department of Energy Orders, Nuclear Waste Policy Act, and other sources which have been identified in section 2 of the CRD.

The codes, regulations, standards, and guides applicable to the design of the Engineered Barrier Segment are identified in section 2 of the EBDRD. The principle regulatory requirements are the technical requirements for the Engineered Barrier Segment design. The regulations that the Engineered Barrier Segment/Waste Package must meet are primarily those provided in the following table.

Table 1-1 Federal Regulations Providing a Basis for Requirements

Identifier	Title or Description
10 CFR 20	Standards for Protection Against Radiation.
10 CFR 60	Disposal of High-Level Radioactive Waste in Geological Repository.
10 CFR 960	General Guidelines for Recommendation of Sites for Nuclear Waste Repositories.
40 CFR 191	Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Waste.

1.2 Scope

The Waste Package Development Technical Document (WPDTD) will describe the technical strategy for developing the Waste Package Subsystem Design as well as leading the testing, modeling and evaluation of EB Segment materials with waste isolation functions through Viability Assessment and License Application. The strategy for addressing regulatory, licensing and fabrication issues will be outlined. This document will provide guidance for execution and will describe the essential elements of the Waste Package development program, including the objectives, technical strategy, and approach. The Waste Package Development Technical Document will be revised as necessary to incorporate changes in the Mined Geological Disposal System (MGDS) development program.

1.3 Inputs and Assumptions

As stated in the Scope, the WPDTD will describe the technical strategy for developing the Waste Package Subsystem Design through Viability Assessment and License Application. This informational document is a tool for short-range and long-range planning and is not intended to provide direct input into other technical documents or analysis. No quality-affecting inputs or assumptions have been used in the development of the WPDTD. The *Controlled Design Assumptions Document (CDA)*(CRWMS M&O, 1995a) contains assumptions which have been used in the development of the EB Segment during Advanced Conceptual Design (ACD). The function of the CDA document (or a possibly similar replacement) will remain unchanged until key requirements have been identified and baselined. A more detailed explanation of QA applicability is provided in Section 2.0. Interfaces involved in the development of this document are documented in the references.

1.4 Description of the Waste Package Subsystem

There are two sets of nomenclature used throughout this document. One set is of a generic nature and is used mostly when discussing high-level program requirements and direction and when talking in general terms. (An example of which is the generic term "repository" as used to refer to the entire disposal site and operation, and the engineered barrier system as defined by 10 CFR 60.) The second set is more specific to the project and reflects the systems engineering approach adopted by the Management and Operating Contractor (M&O) to configure the systems, structures, and components that make up the CRWMS (such as the terms "Repository Segment" and "Engineered Barrier Segment"). These refer to specific Configuration Items as subsets of the MGDS Element (e.g., the Engineered Barrier Segment architecture is shown in Figures 1-1 through 1-3). Generic terms are usually shown in lower case letters. Configuration Items are always shown in initial upper case and end in the given hierarchial words assigned to the Configuration Item architecture structure (e.g., Waste Package Subsystem). Repository Design is the lead in the design and development of the Underground Facility Subsystem. The Waste Package Development and Waste Package Materials organizations will provide input as well as lead the evaluation, testing and modeling of EB Segment materials directly affecting waste isolation capability.

The Waste Package Subsystem will be designed and integrated into the Engineered Barrier Segment through a systems design approach. Figure 1-3 illustrates the Waste Package Subsystem architecture. A description of each Subsystem Element and Component is provided below.

The **Waste Package Subsystem** includes any waste form containers, shielding, and packing and absorbent materials immediately surrounding an individual disposal container.

The Waste Package Subsystem includes the following Subsystem Elements: Uncanistered Spent Fuel (UCF) Disposal Container and Basket, Canistered Fuel Disposal Container, High Level Waste (HLW) Disposal Container, Filler Materials, Shielding, Packing and Absorbent Materials, and Waste Package Support.

The **Waste Container Subsystem Element** is the primary container that holds and is in contact with, solidified high-level radioactive waste, spent nuclear fuel, or other radioactive materials and any overpacks that are emplaced at a repository.

The Waste Container Subsystem Element includes the following Components: UCF Disposal Container and Basket, Canistered Fuel Disposal Container, HLW Disposal Container and Filler Materials (if required).

The **UCF Disposal Container Component** is a disposal container containing a fuel basket. The UCF disposal container is employed only at the repository for the disposal of uncanistered (bare) commercial pressurized water reactor (PWR) and boiling water reactor (BWR) (SNF) assemblies. Such assemblies would originate from: SNF sent to the repository in bare fuel transportation casks, and/or the contents of any canistered fuel canisters found unsuitable for disposal. The UCF disposal container includes but is not limited to: multiple containment barriers, basket members, optional neutron absorber material, internal thermal shunts, supports for the basket, and multiple closure lids. Criticality control alternatives include: neutron absorber material alloyed with the basket material, addition of neutron absorbing panels or control rods, and/or addition of filler material for moderator displacement (to aid in criticality control).

The **Canistered Fuel Disposal Container Component** includes all items which form a disposal container for SNF waste forms packaged in a canister. The Canistered Fuel Disposal Container Subsystem Element includes but is not limited to: multiple containment barriers and multiple closure lids.

The **HLW Disposal Container Component** includes all items which form a disposal container for processed high-level waste forms packaged in waste canisters originating from: Savannah River, Hanford, Idaho National Engineering Laboratory (INEL), West Valley, and other locations supplying process waste for disposal. The HLW disposal container includes but is not limited to: multiple containment barriers, multiple closure lids, and internal structure.

The **Filler Materials Component** (if needed) includes all filler materials and equipment used to fill the voids remaining in disposal containers after loading of high-level nuclear waste. Filler materials may be used for neutron absorption, moderator displacement, chemical buffering and/or radionuclide transport retardation. The most likely application would be addition of filler material to selected SNF waste packages for the purpose of moderator displacement to aid in criticality control. Filler material may also be added for the disposal of HLW waste packages. The equipment includes but is not limited to: hoppers, chutes, piping, associated fittings, valves, quantity measuring equipment, and ancillary equipment necessary for adding filler material to disposal containers.

The **Waste Package Support Subsystem Element** includes the components necessary to support and stabilize the disposal container structurally when emplaced in the repository. The items in this subsystem are those items which: 1) are in immediate contact with the emplaced disposal container (or shield, if included), and 2) will remain permanently emplaced in the drift with the waste package. The items in this subsystem include but are not limited to: cradles used to support the disposal container/shield, and any associated tie-downs to restrain movement of the disposal container/shield.

The **Shielding Subsystem Element** (if needed) includes any material that provides radiation protection, beyond the limited shielding inherently provided by the disposal container, which will be disposed of as part of the waste package. This configuration item excludes any shielding which is not an integral part of the waste package (i.e., overpacks necessary for transport or use within containment buildings where waste packages are handled or stored).

The **Packing and Absorbent Materials Subsystem Element** (if needed) includes any items or materials immediately surrounding an individual disposal container which inhibits the release of radionuclides to the accessible environment.

The **Underground Facility Subsystem** is that portion of the Engineered Barrier Segment that has been allocated the primary function of limiting radionuclide transport.

The Underground Facility Subsystem includes the following subsystem elements:

Emplacement Drift Openings,
Emplacement Drift Backfill Materials
Emplacement Drift Invert

The **Emplacement Drift Openings Subsystem Element** includes the space from which rock has been excavated; where waste is to be emplaced, specifically excluding all other excavated spaces.

The **Emplacement Drift Backfill Materials Subsystem Element** (if needed) includes all backfill materials placed in the waste emplacement drifts as an engineered barrier for the purpose of containing and isolating the waste from the accessible environment. Backfill may be used to retard the migration of radionuclides from the waste package to the geologic setting.

The **Emplacement Drift Invert Subsystem Element** consists of the material or inverted arch placed at the bottom of the emplacement drift to provide a floor with a configured and usable surface. The Invert includes the invert materials placed in the waste emplacement drifts as an engineered barrier for the purpose of containing and isolating the waste from the accessible environment. The invert will assist in retarding the migration of radionuclides from the waste package to the geologic setting. The invert also provides structural and mechanical functions for the construction and operation of the Repository.

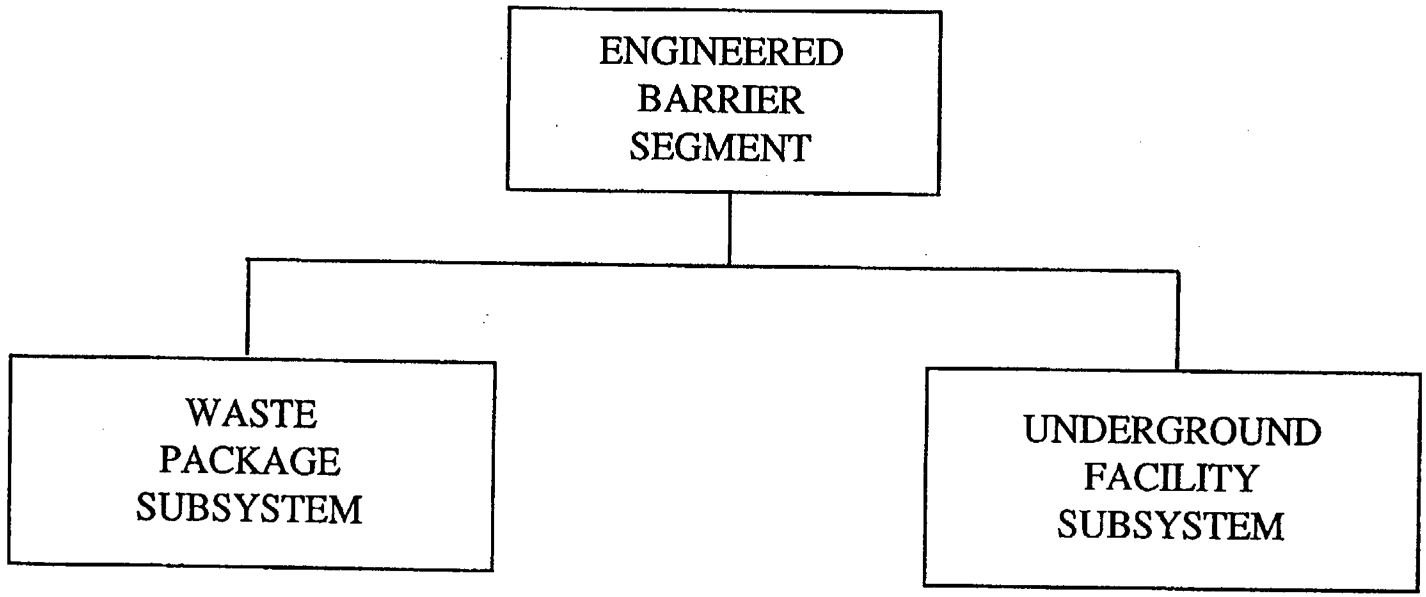

Figure 1-1 Engineered Barrier Segment

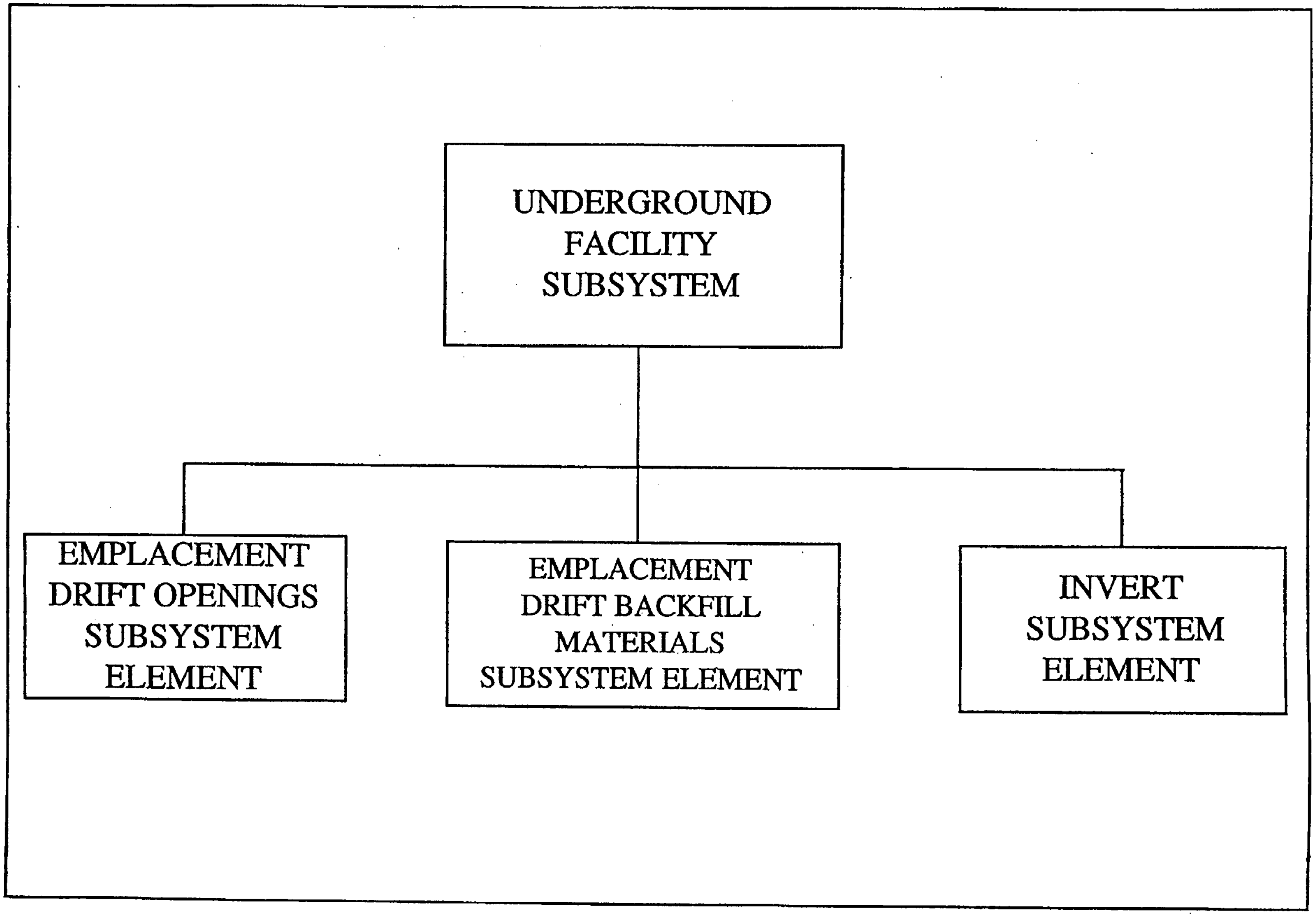

Figure 1-2 Underground Facility Subsystem

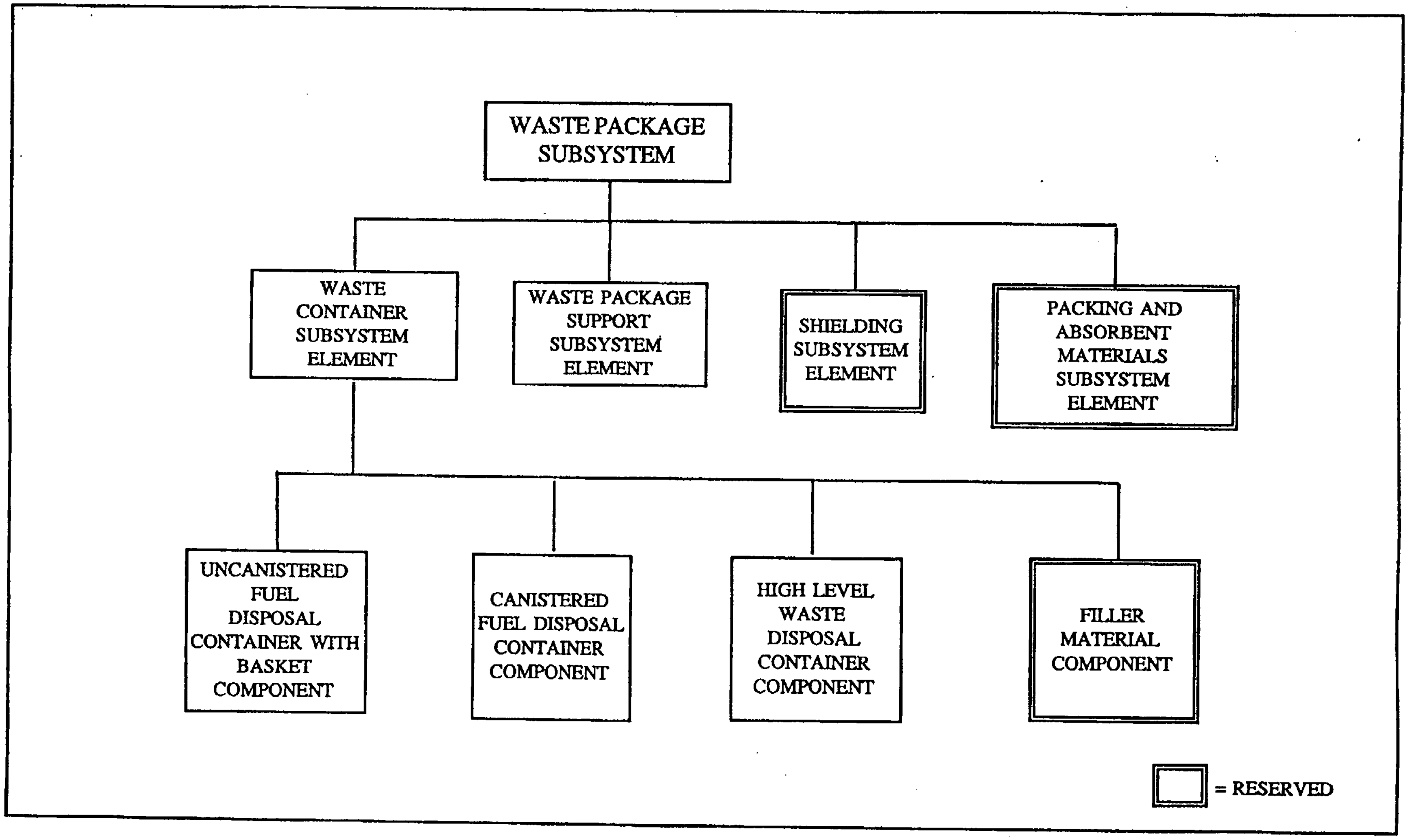

Figure 1-3 Waste Package Subsystem Architecture

2.0 QUALITY ASSURANCE

The quality assurance requirements are defined in the *Quality Assurance Requirements and Description*(QARD) (DOE, 1995), and implemented through the use of approved procedures. The QARD describes the activities for which quality assurance shall be applied. Other activities, such as scoping activities, will be performed using standard engineering practices, unless more stringent practices are required by management.

The Quality Assurance (QA) program is applicable to the overall Waste Package Subsystem Development task. The Waste Package Subsystem has been identified as an item on the MGDS Q-List by direct inclusion by the Department of Energy. A Quality Administrative Procedure (QAP)-2-3 classification analysis has not yet been performed. Furthermore, an NLP-2-0 Determination of Importance Evaluation (DIE) is not applicable to the Development of the Waste Package Subsystem. The subtasks associated with Waste Package Subsystem Development and their QA applicability have been defined by the QAP-2-0 Activity Evaluations listed in the Appendix. The applicable QAPs are identified for each task.

All information relating to the design, design analysis, testing, and Performance Assessment (PA) of the WP and Engineered Barrier System that will form a basis of the license application will be acquired or developed in accordance with the QARD. To this end, all participants in the YMP have developed or adopted QA procedures that reflect all requirements of the QARD including the control of software.

This document is being developed for strategic planning only therefore does not require qualified inputs. No scientific or engineering software has been used in the development of this document. This document is related to a MGDS Q-List item and its development is controlled under the Activity Evaluation, Formal Review of Technical Documents (BB0000000-01717-2200-00007 Rev 02).

This document describes work that affects items on the YMP Q-List, YMP/90-55, and changes to this document shall be controlled in accordance with applicable M&O quality assurance procedures. The plan will be revised as necessary to reflect changes in upper-tier documents, including the requirements of the Engineered Barrier Design Requirements Document, (YMP, 1994).

3.0 REQUIREMENT COMPLIANCE

3.1 Licensing Goals

The principal goal of the development effort is to create a Waste Package Subsystem design that will be licensable; i.e., it will meet the requirements with sufficient margin so that the NRC will find that compliance has been achieved with reasonable assurance.

Performance will be allocated to each barrier in the system. As shown in Figure 3-1, performance allocation leads to the establishment of performance measures and parameter goals that are

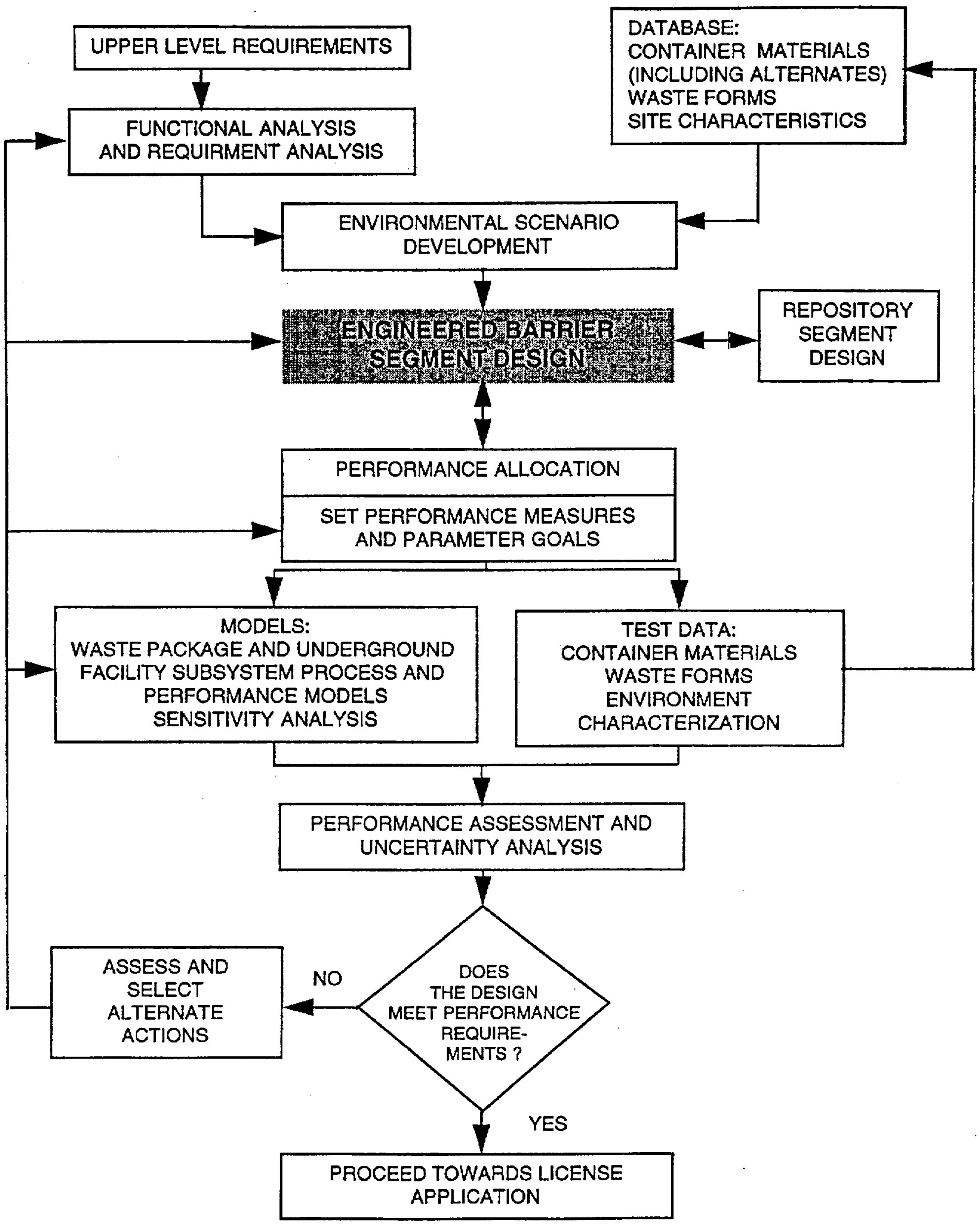

Figure 3-1 Engineered Barrier Segment Development Strategy

reevaluated as test data and predictive models are developed. The goal of the EB Segment waste isolation materials testing program is to develop sufficient understanding of materials and component behavior to guide the design effort, and to provide adequate data to support modeling of the performance parameters, i.e., to provide reliable models.

3.2 Licensing Approach/Assumptions

Regulatory compliance will be demonstrated by a performance assessment of the MGDS Element. The performance assessment will entail solving detailed parametric mathematical representations of the MGDS Element. The MGDS Element comprises of the Site, Repository and EB Segments. These segments will be simulated by submodels which will provide data for complete MGDS models. These models and submodels will be simulated with the use of QA-validated computer codes.

The approach to licensing recognizes that full model validation is not possible due to the long service life of the WP Subsystem. However, the licensing approach will include several activities that support the validation effort. These may include: in situ testing of full or sub-scale prototypes of WP Subsystem designs in the Exploratory Studies Facility or another test facility; the evaluation of natural analogues, particularly for corrosion-allowance and ceramic materials; and the use of the American Society for Testing and Materials (ASTM, 1991) framework for testing and modeling of material responses.

3.3 Environmental Scenarios/Conceptual Models

As noted in Subsection 3.1, the WP Subsystem will be designed to be environment tolerant. Thus, variations in temperature, moisture level, and water chemistry will be considered. However, assumptions still need to be made and documented in the Controlled Design Assumptions document regarding the range of environmental conditions in the repository including the pre-emplacement undisturbed condition, the post-emplacement disturbed condition, and the condition following closure. In addition, the potential modes of water contact with the package for the design concepts being evaluated must be assessed. For most design concepts, the moist-continuous, wet-drip, and steam-air modes must be evaluated. Which of these modes is dominant is dependent on the thermal loading of the repository and the thermal properties of any backfill. Under a thermal loading in the 80-100 MTU/acre, the repository will initially be hot and dry (low relative humidity). As the waste packages cool, the relative humidity will slowly increase.

Conceptual design and repository response models have been described in the MGDS ACD Report to provide a means for preliminary comparison of design concepts and to direct the formulation of the performance parameters and component performance allocations. These conceptual models also serve as an aid in the design of testing programs by identifying key physical and/or chemical processes, thus focussing test methodologies and goals. These conceptual models also feed the development of the mechanistic models/submodels needed for performance assessment.

3.4 Performance Allocation

Performance allocation is a tool for developing a design of the WP Subsystem that meets applicable performance requirements. Containment and radionuclide release performance requirements are assigned to the components of the system. The capability of these elements to meet the allocations will be demonstrated through performance assessment of the system supported by test data obtained in accordance with Scientific Investigation Plans (SIPs). Note, however, that performance assessment is focused on the total system, rather than the subsystem, performance.

Performance measures will be based on requirements with the SCP utilized as a guide. The performance measures appropriate to the development of the WP Subsystem, which have been evaluated and updated, are discussed in Section 4.0, Technical Approach.

For the containment period, a multibarrier design that is environment tolerant permits performance allocation for isolation to be allocated to the Engineered Barrier Segment, rather than the Repository Segment. For example, the quantity and chemical variability of liquid water that is assumed to contact the containers has been expanded. This multibarrier design includes both a corrosion-resistant and a corrosion-allowance material. The final design configuration will depend on the range of environmental conditions chosen as a design input. Thermal analyses will be performed to determine the temperature profiles across the drifts for drift emplacement. These analyses will permit the re-evaluation of the goals given in the SCP for performance measures. All of the preliminary allocations provided in the SCP will be reviewed. These will be confirmed as an interactive result of the scientific investigations, design and performance assessment.

Similarly, the subsystems to which performance is allocated during the post-containment period will be reviewed. The performance allocated to the natural barrier and the container will be modified or reallocated after the possible addition of backfill materials, particularly for drift-emplaced WPs. Filler materials, which are being considered in the design of spent fuel and HLW WPs, can add mechanical stability during handling, provide a chemical buffer to condition the interior of the package, assist in criticality control, and may provide a diffusional resistance to migration of radionuclides.

Performance parameters are the in-repository responses of the WP Subsystem and its components which affect the ability to meet their performance measure allocations. A determination of these parameters has been documented in the SCP (DOE, 1988) and the SIPs. These will be reviewed for consistency with the ACD design concepts. Parameters will be identified and confirmed for performance assessment of the selected reference designs. These are discussed in detail in Section 4.0.

4.0 TECHNICAL APPROACH

4.1 Introduction

This section describes the detailed technical approach to developing a WP Subsystem design which will meet requirements and ultimately can be shown to demonstrate regulatory compliance. This approach involves the integration of design development, materials/component testing, repository response modeling, and performance assessment. Development of reference and alternative WP designs takes into account the mechanical and other properties of the components and the ability to manufacture and assemble them, the cost to produce them and the ability to predict their performance under repository conditions. The design, testing, and performance assessment activities are integrated and iterative.

This document relates the rationale for test activities to the need to provide WP material/component response models applicable for repository time scales from relatively short-term testing. The required degree of extrapolation makes development of reliable models difficult. Test programs will distinguish between addressing performance parameters, which are responses in the repository environment and which require applicable models, and attributes, which are inherent characteristics independent of environment. One approach to bridging this extrapolation gap was outlined in ASTM Procedure C1174, *Standard Practice for Prediction of the Long-Term Behavior of Waste Package Materials Including Waste Forms Used in the Geologic Disposal of High-Level Nuclear Waste* (ASTM, 1991). This approach will be used to address the generation, justification, and validation of models, and the minimization of uncertainties in the long-term extrapolation of the models developed from the test data. The approach is detailed in later portions of this section.

The framework for the development of the Waste Package Subsystem (including waste isolation materials) technical approach is presented in Table 4-1. Table 4-1 details functions, performance measurements, degradation modes, and performance parameters associated with EB Segment Components. This framework is based on the anticipated combination of EB Segment components and their respective functions. Component functions have been assigned to each anticipated EB Segment component on the basis of the need to satisfy regulatory requirements to contain and subsequently limit the release of radionuclides. As the EB Segment design evolves, components and associated functions may be added or deleted from this table. The design of each component must focus on the particular functions of the component and its interface with other components or functions.

For each identified component function, performance measures are identified. The performance measures are the means by which component performance is measured. The performance measures are used to quantify "how well" the component is anticipated to perform its functions. Quantification is accomplished using component models that will be developed (based on simplified and combined degradation mode models) to predict each performance measure. Performance measures will also be captured in System Design Documents (SDDs) during the VA phase.

For each component performance measure, degradation modes are identified that influence the performance measure. Degradation modes are material behavior forms or processes that can result in an adverse change in the quantitative level of a performance measure. Degradation mode models will be developed based on a fundamental, mechanistic understanding of the processes associated with the degradation. If mechanistic understanding cannot be developed, a semiempirical model will be developed.

In some instances where assumptions can be justified on a scientific basis, it may be judged prudent that an empirical, bounding model approach be used. Degradation mode models will be simplified and combined to develop the component models used to predict the performance measures described above.

For each degradation mode, performance parameters have been identified. The performance parameters are either intrinsic or extrinsic properties or attributes of the EB Segment materials that combine to result in the respective degradation modes. It is important to develop, to the extent practical, a mechanistic understanding of the processes associated with the performance parameters to aid in the development of defensible degradation mode models.

The materials testing effort must focus on the generation of these performance parameters or on the data that can be used to establish the parameters. The performance parameters need to be understood over the range of environmental conditions expected throughout the component's service lifetime. The model development effort must focus on the particular performance measures identified for each component. Models must be developed that will permit calculation of the performance measures for performance assessment purposes.

The WP Subsystem Design, Materials Testing, and Performance Assessment Sections detail the integrated technical approach to development of a WP Subsystem design and materials testing, modeling and evaluation that demonstrates compliance with the requirements.

Table 4-1 Technical Approach to Engineered Barrier System Development* (Page 1 of 3)

EB SEGMENT COMPONENT	WASTE ISOLATION FUNCTION OF COMPONENT	PERFORMANCE MEASURE	DEGRADATION MODE	PERFORMANCE PARAMETER
EMPLACEMENT DRIFT BACKFILL	Limit water Contact with WPs	Fraction of WPs Contacted by Water	Water Flow Through the Backfill	• Hydraulic Conductivity of Backfill • Backfill Heterogeneity
	Distribute Rock Loads Imposed on WPs	Stresses Induced in WP Components by Rock Loading	Load Transmittal Through the Backfill	• Backfill Compaction (%) • Initial Backfill Density • Consolidated Backfill Density • Backfill Settlement (%)
	Limit Radionuclide Egress from EB Segment	Release Rate of Radionuclides from EB Segment	Air Pathways	• Hydraulic Conductivity of Air in Backfill • Diffusion Coefficients of RNs in Air
			Water Pathways	• Hydraulic Conductivity of water in Backfill • Diffusion Coefficients of RNs in water • Retardation Coefficients in Backfill
	Provide Acceptable Heat Transfer	WP Peak Cladding/Surface Temperature		• Thermal Conductivity
EMPLACEMENT DRIFT INVERT	Limit Radionuclide Egress from EB Segment	Release Rate of Radionuclides from EB Segment	Water Pathways	• Hydraulic Conductivity of water in Backfill • Diffusion Coefficients of RNs in water • Retardation Coefficients in Backfill
METALLIC CONTAINER	Contain Radionuclides	Fraction of Containers Breached	Metallurgical Instability (incl. weld and HAZ)	• Phase Transformations
			Low-Temperature Oxidation	• Oxidation Rates
			General Aqueous Corrosion	• General Corrosion Rates
			Microbiologically Influenced Corrosion (MIC)	• MIC Rates
			Pitting Corrosion	• Ecrit for Pitting • Eprot for Pitting • Pit Penetration Rates
			Crevice Corrosion	• Penetration Rates

*Table inputs are either taken directly or are derived from the SCP (DOE, 1988).

Table 4-1 Technical Approach to Engineered Barrier System Development* (Page 2 of 3)

EB SEGMENT COMPONENT	WASTE ISOLATION FUNCTION OF COMPONENT	PERFORMANCE MEASURE	DEGRADATION MODE	PERFORMANCE PARAMETER
METALLIC CONTAINER	Contain Radionuclides	Fraction of Containers Breached	Environmentally Assisted Cracking	• Crack Propagation Rates • Threshold Stress Intensity Factors (KsubSCC)
			Mechanical Instability	• Tensile Properties • Creep Properties • Fracture Toughness (Jsub1C)
	Limit Radionuclide Egress after Container Breach	Release Rate of Radionuclides from Container	Diffusion Through Corrosion Products	• Diffusion Coefficients of RNs in Corrosion Products
			Transport Through Cracks	• Diffusion Coefficients of RNs in Groundwater • Crack Geometry • Eff. Hyd. Cond. of Breached Container
NON-METALLIC CONTAINER	Contain Radionuclides	Fraction of Containers Breached	Chemical Dissolution Mechanical Instability	• Dissolution Rates • Tensile Properties • Creep Properties • Fracture Toughness
	Limit Radionuclide Egress after Container Breach	Release Rate of Radionuclides from Container	Transport Through Cracks	• Diffusion Coefficients of RNs in Groundwater
			Gaseous Diffusion	• Carbon(14) Dioxide Diffusion Coefficients in Non-Metallic
SNF BASKET	Prevent Criticality	WP K_{eff}		• Boron Concentration
	Enhance Heat Transfer	WP Temperature Gradient		• Thermal Conductivity

*Table inputs are either taken directly or are derived from the SCP (DOE, 1988).

Table 4-1 Technical Approach to Engineered Barrier System Development* (Page 3 of 3)

EB SEGMENT COMPONENT	WASTE ISOLATION FUNCTION OF COMPONENT	PERFORMANCE MEASURE	DEGRADATION MODE	PERFORMANCE PARAMETER
SNF CLADDING	Contain Radionuclides	Fraction of Fuel Rods Breached	Low-Temperature Oxidation General Aqueous Corrosion Pitting Corrosion Mechanical Instability	• Oxidation Rates • General Corrosion Rates • Pit Penetration Rates • Creep Rupture Properties (Includes Hydride Formation Effects)
SPENT UO_2	Limit Radionuclide Release from UO_2	Release Rate of RNs from UO_2	Pellet-Cladding Gap Exposure	• Activity of C-14 Released as a Gas • RN Concentrations in Contacting Water
			Spent Fuel Oxidation	• Activity of C-14 Released as a Gas • Higher Oxide Formation Rates
			Spent Fuel Dissolution (Matrix and Grain Boundary)	• Activity of C-14 Released as a Gas • RN Concentrations in Contacting Water
METALLIC HLW GLASS CANISTER	Contain Radionuclides	Fraction of Canisters Breached	Metallurgical Instability (incl. weld and HAZ)	• Grain Boundary Sensitization
			Low-Temperature Oxidation	• Oxidation Rates
			General Aqueous Corrosion	• General Corrosion Rates
			Pitting Corrosion	• Pit Penetration Rates
HLW GLASS	Limit Radionuclide Release from Glass	Release Rate of RNs from Glass	Glass Dissolution	• RN Concentrations in Contacting Water

*Table inputs are either taken directly or are derived from the SCP (DOE, 1988).

4.2 Waste Package Subsystem Design

This section includes guidance on the methodology and criteria for the selection and prioritization of WP designs. This section describes the WP design process; summarizes the progress made during the Advanced and Conceptual Design Phases; and provides an overview of the Viability Assessment and License Application Phases. For more detailed information on Waste Package Subsystem/EB Segment development work competed during the ACD phase of development, refer to Volume II and III of the *Mined Geologic Disposal System Advanced Conceptual Design Report* (CRWMS M&O, 1996a).

The system design process will relate design parameters (such as materials selections and design configurations) to performance allocation, thereby integrating design with the testing and modeling activities. It will link conceptual candidate waste container fabrication processes with design, performance parameters, and performance allocation requirements (in terms of predictive models and the testing required to support the models).

The principal goal of the WP development effort is to create fabricable and cost effective WP designs that will be licensable and will accommodate canistered and uncanistered spent fuel, HLW glass, and other authorized waste forms as stipulated by the DOE. The designs will meet the regulatory requirements with sufficient margin that the NRC will find that compliance has been achieved with reasonable assurance.

4.2.1 Selection Criteria

Each design concept includes a number of options that are driven by the requirements and functional needs. The matrix of options, shown in Table 4-2, is a list of options that can be used in combination to define various WP concepts. For example, an emplacement mode may be selected and then a given set of barrier options could be chosen, then material options can be selected.

The selected WP concepts that are derived from the matrix were evaluated during ACD. Detailed engineering design activities, including thermal, structural, neutronic, and fabrication activities, will be performed. Materials will be evaluated and selected and analytical models will be developed to assess the design concepts. At the start of the Viability Assessment, a conceptual design will be selected for further development. During License Application, full size prototypes may be fabricated and fabrication processes will be finalized along with final engineering and performance analyses. At the end of License Application Design the engineering and performance analyses will be compiled and issued as part of the license application document.

a. The WP Subsystem selection criteria are a composite of how the design concept performs within the system and to what extent the concepts meet/exceed the requirements. General selection criteria are:

- Does the concept meet the federal regulations?
- Does the concept meet the WP design requirements?
- Does the concept meet the system interface requirements?
- Does the concept meet the design goals?

b. For each design concept, a review of the WP system will be performed including how each component functions within the system. A decision tree will be constructed that will include:

- The controls (design and system requirements, federal regulations);
- The inputs (what is needed to perform the design activity);
- Resources/mechanisms (references, test data, etc.); and
- Output (what will be the result of the task/design and where does it lead.)

c. The preclosure WP functional requirements are specified as follows:

- To contain waste during handling, storage, emplacement, and retrieval, if necessary;
- To prevent criticality within the WPs; and
- To provide a means of unique identification.

4.2.2 Concept Development

The number of conceptual designs was narrowed during the Pre-ACD and ACD phases, with final selection taking place early in the Viability Assessment phase.

4.2.2.1 Pre-ACD and ACD

An important activity during the Pre-ACD phase was the identification of a reduced set of conceptual designs for detailed evaluation during ACD. Table 4-2 outlines the various options developed during Pre-ACD. The designs developed in the Pre-ACD Phase were further developed and analyzed during ACD. Table 4-3 lists the design concepts selected for further development in the VA Phase.

Table 4-2 Waste Package Design Options

1.0	Container Type
1.1	Single Purpose
1.2	Dual Purpose
1.3	Multi-Purpose
2.0	Emplacement Modes
2.1	Vertical Borehole
2.2	Horizontal Borehole
2.3	Drift Emplacement
3.0	Barrier Types
3.1	Backfill-Emplacement Drift and Invert
3.2	Packing
3.3	Overpack
3.4	Containers
3.5	Fillers
3.6	Waste Forms
4.0	Material Options
4.1	Corrosion Allowance Materials
4.2	Corrosion Resistant Materials
4.3	Metallic Particulates
4.4	Ceramic Particulates
4.5	Ceramic Monoliths
4.6	Composites
4.7	Earthen Materials (Tuff, Clay, Sand, etc.)
4.8	Cementitious Materials
5.0	WP Capacity/Size
5.1	Three Pressurized-Water Reactor (PWR) Assemblies or less
5.2	Four PWRs
5.3	More than Ten (12 and 21) PWRs
5.4	Equivalent Boiling Water Reactor (BWR) Packages
5.5	Hybrid Package
5.6	Number of Glass Canisters
5.7	Degree of Self Shielding

Table 4-3 Waste Package Advanced Conceptual Design Concept Families*

• Canistered SNF Disposal Container
• Uncanistered SNF Disposal Container
• HLW Disposal Container

4.2.2.2 Viability Assessment Phase

Viability Assessment (VA) will include a set of four tasks: designs for the Repository Segments and Waste Package Subsystem, a total system performance assessment (TSPA), a license application plan and repository cost and schedule estimates. At the conclusion of the VA Phase, a decision will made regarding the viability of the site. If the decision is favorable, the same body of work will ultimately serve as a foundation for a license application to the NRC. Waste Package Development tasks will be key to each part of the Viability Assessment Phase:

Engineered Barrier Segment Design

Waste Package Development will address design elements that are critical to determining the feasibility and performance of the Engineered Barrier Segment. The technological feasibility of the designs will be evaluated, but the detail needed for licensing will not be completely developed until the LA Phase. The designs will build on previous work, with emphasis placed on key technical questions that affect performance and cost. These questions, based on waste isolation and containment strategy, revolve around thermal management of the waste generated heat, the role of supplemental engineered barriers, corrosion of waste packages, and dissolution of radioactive wastes. In addition, the safety systems and other factors that significantly affect Engineered Barrier Segment costs will be addressed.

Total System Performance Assessment

Performance Assessment is an analytical technique that uses computer models of physical processes to evaluate the degree to which the repository will contain and isolate waste. The MGDS Element's ability to contain and isolate wastes will depend on the characteristics of the natural and engineered barriers. Mathematical models of the physical processes that affect waste containment and isolation (such as groundwater flow) are abstracted and linked to one another to develop an estimate of the overall performance of the repository.

The Waste Package Development and Materials organizations will provide WP Subsystem design input to TSPA. The design input is in addition to process models developed from long and short duration materials testing and long and short-term waste form testing. The process models contribute to performance assessment and hence, Viability Assessment TSPA .

License Application Plan

The third component of the 1998 Viability Assessment will define scope, schedules, and remaining work required to complete a license application. The goal of submitting and docketing a license application to the NRC, contingent on a favorable outcome to VA, remains central to the Program's mission.

The license application plan will describe the information needed for the NRC to review the Program's repository construction request. A key portion of this information will draw on the models and data that describe the WP Subsystem design and the waste containment and isolation strategy. The plan will also identify additional design activities needed to support license application.

Repository Cost and Schedule Estimates

The cost and schedule estimates of the MGDS Element will address construction, operation and closure of a repository at Yucca Mountain, based on the data available at the conclusion of VA. As an Engineering Development task, Waste Package Development will update existing cost estimates. Input will be developed and provided for the scheduling portion of this component of VA.

4.2.2.3 License Application Phase

The License Application Phase of the Program completes the evaluation of concepts developed during the Viability Assessment Phase and selects the final two (primary and alternative) SNF designs and the final HLW glass design. Each design will be investigated in detail from the performance and manufacturing points of view. The LA designs will be based on the sum of the data gathered or generated. The evaluations will build from the VA designs and will incorporate any comments that have been received from the other system elements. Design and fabrication studies will continue. The results of the LA evaluation will include:

- Analytical design report(s)
- Technical Drawing Packages
- Design specifications
- Material specifications
- Fabrication drawing Packages
- Fabrication specifications
- Manufacturing development report(s)
- License Application Section on WP Subsystem designs and fabrication.
- In service Inspection Recommendations

The License Application Phase also includes the completion of material and waste form testing and modeling and its documentation.

4.2.3 Design Tools (Commercial Standards, Codes, Specifications, Regulatory Guidance)

The design process will use industrial and nuclear design, material and fabrication standards.

Additional industrial standards will be used as guides. Only those sections that are directly applicable to the WP Subsystem will be used. NRC and DOE guidance and precedence will also be incorporated as a design tool where appropriate. Table 4-4 lists examples of commercial codes and standards which may have direct applicability to the WP Development program.

Table 4-4 Commercial Codes and Standards

Identifier	Title or Description
ANSI/AND	Standards: 8.1, 8.3, 8.5, 8.7, 8.9, 8.10, 8.12, 8.13, 8.15, 8.17, 8.20, 57.2, 57.3, and 57.7. American National Standards Institute/ American Nuclear Society
ASME 1992	1992 ASME Boiler and Pressure Vessel Code, Section II, American Society of Mechanical Engineers, 1992

4.2.4 Design Analyses

Regulatory requirements, waste form, materials selection and process concerns, and the results from the neutronic, thermal, and structural evaluations have a major influence upon evolution of the waste package conceptual designs. In turn, the features of the design concepts then influence the materials, neutronic, thermal, and structural evaluations, resulting in an iterative approach to waste package design evolution. The following sections provide an overview of the three main types of design analyses required for Waste Package Design.

4.2.4.1 Neutronic Evaluations

Neutronic evaluations encompass two major areas: radiation shielding and criticality control. In both areas, analyses depend upon definition of design basis waste form characteristics, namely: initial level of fuel enrichment, fuel burnup, and age of the fuel (since removal from the reactor). The characteristics of existing spent fuel and fuel projected to exist in the future are not of a singular population, but in fact the characteristics are quite variable. This leads to the necessity of examining and establishing sets of spent fuel characteristics for purposes of waste package design and repository design.

Neutronic evaluations employ computer codes to perform calculations of isotopic composition, source determination, depletion rate, radiation shielding, and criticality safety. The neutronic computer codes require supporting data libraries with nuclear isotopic cross sectional data and isotopic decay data. To perform various neutronic evaluations and parametric studies, several codes will often be used in combination.

Neutronic evaluations will include analysis of waste package design concepts and of canistered fuel canisters placed within disposal containers. Results of the evaluations would be expected in turn to have an impact upon the waste package design. The other areas of waste package design depend on the various results from neutronic evaluations, including: design basis fuel definitions, radiation shielding requirements, quantification of the neutron absorber needed within the waste package basket to provide criticality control, uncertainties associated with using fuel burnup credit, the decision of flux trap versus burnup credit design, and the need for waste package filler material to provide moderator displacement or chemical buffering for radionuclides.

4.2.4.2 Thermal Evaluations

Decay heat generation by nuclear waste materials affects the waste disposal repository in several ways. The total thermal output of any waste package design is a function of a number of factors, including the type, quantity, enrichment, and burnup age of the waste form. Variation of any of these factors, and thus heat output, requires parametric thermal studies of various repository parameters, including: waste package capacity, size of drift, shape of drift, waste package position within a drift, waste package spacing and drift spacing. The effect of emplacement backfill on peak fuel temperatures must also be analyzed. Thermal loading studies will focus on a reference thermal loading of 80-100 MTU/acre.

Increasing the number of SNF assemblies within a waste package results in increased internal temperatures. Limitations upon fuel rod cladding temperature will have the effect of limiting the number of assemblies per waste package. However, cladding temperatures will be dependent upon design of the waste package internal basket, and also upon whether a filler material is to be used within the waste package.

Thermal evaluations are dependent upon information to be provided by others, both from within the Waste Package Development and Waste Package Materials organizations and from other organizations. Examples of required input include:

- Disposal Container and Basket Designs
- Material Properties
- Emplacement Drift Configuration and Dimensions
- Host Rock Properties
- Potential Change of Near-field Host Rock Properties Resulting from Long-term Temperature Effects
- Determination of Whether Fuel Burnup Credit Is to be Allowed
- Definition of the Thermal Design Basis Spent Fuel and HLW
- Configuration and Characteristics of Canistered Fuel Canister Designs
- Waste Package Fill Gas Properties (if used)
- Filler Material Properties (if used)

4.2.4.3. Structural Evaluations

Structural evaluations will primarily be of the waste package multibarrier shells and the internal basket. Handling loads will be incurred from activities ranging from waste package filling operations to emplacement within the repository. External loadings may result from drop tests, seismic activity, rock fall, and ground support material onto the waste package in the repository prior to backfilling the drifts. Additional evaluations will include long term effects relating to thinning of the barrier(s) due to corrosion and the imposition of plausible long term external loading upon those barriers.

Structural evaluations depend upon inputs from others regarding actual waste package design configuration, waste package thermal conditions, definition of external loadings due to drop or rock fall, etc. Results of the evaluations would be expected in turn to have an impact upon the waste package design.

4.2.5 Engineering Development Tasks

4.2.5.1 Purpose

The purpose of the Waste Package Engineering Development tasks is to perform the requisite engineering development and manufacturing process development for fabrication, closure, and inspection of Waste Container Subsystem Elements. This includes the UCF (with basket), CF, and HLW Disposal Container Components and the Filler Material Subsystem Element. The engineering development tasks will complement not only the waste package design evaluations, but also Engineered Barrier Segment design and performance assessment. These tasks will focus on the waste package designs which evolve from the various discipline studies such as thermal, neutronics, handling and emplacement, etc.

The sizes and wall thicknesses of the disposal containers will require consideration of a range of manufacturing processes, as a result of limitations of those various processes. Similarly, a range of container closure design configurations and welding techniques will also be considered, driven by concerns of weld-induced stress minimization, the possibility of post-weld stress reduction treatment, and by non-destructive examination (NDE) inspection capability and limitations. Technical feasibility and cost effectiveness of the various fabrication and closure concepts will be the focus of the engineering development tasks during the VA phase of the program. Throughout the VA and LA phases, the manufacturing processes and their associated cost will be developed in more detail. During the LA Phase, this work will focus on the UCF (with basket), CF, and HLW disposal container design.

The Engineering Development process is based on a proven Industrial Engineering process (Roberts, 1983). The Engineering Development process provides a disciplined and systematic approach to manufacturing, including a method of identifying key development tasks. The Engineering Development process and experience was used to identify key development tasks. At present there are five key Waste Package Engineering Development tasks which have been identified:

1) Container and basket fabrication, including stress minimization

2) Remote closure, including weld-induced stress minimization

3) Remote nondestructive examination of closure weld

4) Waste package filler material testing and development

5) Remote in-service-inspection

The engineering development activities associated with each task include:

1) Preparation of a Technical Guidelines Document for each individual task, including interface requirements

2) Review of manufacturing process facilities and/or engineering test laboratories

3) Approval of Test Plans from manufacturing process facilities and/or engineering test laboratories

4) Technical management of manufacturing process development and testing activities

5) Creation of waste package engineering and manufacturing process specifications, based on results of the development tasks

6) Cost Estimating

4.2.5.2 Container and Basket Fabrication, Including Stress Minimization

The objective of this development task will be to develop a method of fabricating the multibarrier disposal containers and basket designs produced by the Waste Package Design organization. The fabrication method will be cost-effective and rely on existing and proven technology. A key component of this task is the minimization of fabrication tensile stresses that are induced during the manufacturing process. The WP design life, and hence the containment time, is intended to be in excess of 1,000 years. To extend the WP containment time, the components must be in a stable and low tensile stress state after manufacturing and closure.

This task will develop a stress mitigation approach that can be applied during manufacturing to produce a compressive residual stress or minimize the residual tensile stresses. The three development approaches and associated objectives are:

a. Closure and fabrication. The objective is to provide guidance in the development of closure and fabrication technology. The task will include the evaluation of low stress fabrication technologies, closure methods and parameters, closure joint configuration, and computer models to support the design and licensing activities.

b. Stress measurement. The objective is to develop a method that can be used to measure the residual stress level of components and assembly.

c. Stress reduction. The objective is to develop techniques that can be applied to the closure and fabrication of the components to further reduce the induced tensile stresses.

The waste package internal basket manufacturing development program will develop fabrication techniques for the several basket design configurations. The results from neutronics analyses will help define the quantity of neutron absorber material required, most likely in the form of an alloy within a base material. The structural use of a neutron absorber material alloyed with a base metal in a basket configuration will be further examined during the VA phase of development. The manufacturing development program will determine methods of fabrication/assembly of the basket, including the process control needed to produce a product with satisfactory geometric integrity to meet specified design clearances (sufficiently square and straight cells). The need for, and methods of affixing the basket within the waste package will also be developed.

The basket manufacturing development program will provide test specimens and subscale mockup fabrications. The conclusion of the testing program will lead to a formal evaluation and drafts of proposed specifications for the selected basket manufacturing processes. During the LAD program phase, manufacturing development will produce several sets of full scale prototype parts for final development and acceptance testing, and will provide the waste package manufacturing development final report and final specification package.

As stated earlier, the disposal containers will not be designed and built to American Society of Mechanical Engineers pressure vessel codes, as the disposal containers do not function as pressure vessels. Disposal container materials will conform to American Society for Testing and Materials standards, and may be specified to be American Society of Mechanical Engineers Code Case materials, but there will be no blanket requirement to use Code Case materials in the disposal containers.

Manufacturing studies will include prototype fabrication and an engineering test series that will be completed on the prototype units and results incorporated into the designs. The test series will determine whether the WP design requirements have been met.

4.2.5.2.1 Cost Estimates

Waste Package fabrication cost estimates are required to support Waste Package Development design comparison and evaluation activities, and to provide input to support program Total System Life Cycle Cost (TSLCC) studies. As part of the WP development process, evaluation of the various WP design concepts will be performed based on both technical feasibility and cost effectiveness of the selected manufacturing processes for disposal container/WP fabrication, as well as for remote closure and remote inspection.

The objective of the interrelated tasks of fabrication, closure, and inspection is to identify, develop, and demonstrate the optimum processes for container manufacturing, consistent with WP functional and performance requirements. The solution is complex because the manufacturing method affects the characteristics and physical properties of the product being produced. These effects must be understood and integrated into the overall development program to achieve selection of both materials and manufacturing methods that will result in technically conservative processes to ensure safety and long-term performance. In this regard, manufacturing costs should not impose sacrifices in construction methodology, i.e., manufacturing cost is a concern but not a top priority.

Cost estimates are limited to the WP fabrication, i.e., production of the canistered fuel disposal container, uncanistered fuel (UCF) WP with basket, and high level waste disposal container. Fabrication entails production of the disposal container/WP, including the loose closure lids. Production costs must include appropriate quality assurance programs and quality control activities.

4.2.5.3 Remote Closure, Including Weld-induced Stress Minimization

The objective of this development task is to select and develop waste package remote closure welding processes which are technically and economically acceptable, and which will also minimize stresses. Viable methods of repairing defective closure welds must also be developed. This remote closure task, as well as the waste package remote NDE inspection task which follows, must be performed in concert with the waste package container fabrication task, due to the strong technical interrelationships between these tasks.

Installation of the waste package closure lids will take place at the MGDS repository surface facility, following placement of the waste within the waste package container. Each of the two closure lids must be separately remotely welded into place and remotely inspected to complete the envelope for each corrosion barrier. The primary development concerns are the combined choice of weld joint configurations and welding techniques to result in lowest possible post-weld tensile stress conditions, and of joint configurations which can be inspected. Various standard industrial remote closure welding processes will be investigated for each of the selected waste package container design configurations (evolved from the previous task). Other areas which must be considered include: quality of the closure welds (weld integrity, and good mechanical properties of the welds and heat affected zones), economy and time involved in making the closure welds (high deposition rate and minimizing amount of weld filler material), fully automatic remote closure welding equipment, the ability to use the same equipment for both the thin inner weld and thick outer weld, the capability of hardening the welding equipment to the anticipated levels of radiation exposure, and viable methods for repair of defective welds or for container replacement if weld repair should be unfeasible.

The fabrication industry is making continual advances in development of fully automatic remote welding equipment and process control to meet the combined challenges of: stricter quality standards, consistent quality and reduced rejection rate, adaptation to computer numerical control, computer monitoring of weld process parameters for quality assurance, cost control and labor cost reduction, improved health and safety standards, increased productivity through improved operating factors, and the expansion of worldwide competition.

This program shares most of the aforementioned challenges. This development task is expected to benefit greatly from recent and near-future automatic remote welding advances, with the expectation that the needed level of technology already exists, or will be available. The implementation and adaptation of that technology to the circumstances of the waste package closure welds is what remains, which is the major endeavor of this development task. The waste package closure circumstances which require complete isolation of the welding activity within a hot cell, in addition to the effects of a radioactive environment on the welding equipment, are circumstances which tend to be outside those of the less stringent industrial welding conditions.

4.2.5.4 Remote Non-destructive Examination of Closure Weld

The objective of this development task is to select and develop (NDE) inspection technique(s) that are technically and economically acceptable, and which can accommodate the selected waste package materials, thicknesses, and geometries. As previously indicated, certain closure configurations may be incompatible with available NDE techniques, thus this task must be performed in concert with waste package closure configuration design activities. The NDE technique(s) finally chosen will have to prove the quality of both inner and outer closure welds for the chosen configuration for each waste package closure joint, both for the LAD prototype welds and for each and every closure weld made during production.

The types and sizes of flaws that might be encountered in the remotely welded joints must be well understood. Ongoing evaluations of weld test samples produced by the recommended weld methods will provide the data base necessary to characterize the weld defects and for subsequent NDE tests. Weld inspection methods must be selected which are capable of detecting the types of defects or flaws potentially produced by the weld method.

The condition of the completed weld (contour, surface finish) must be compatible with the inspection techniques. Post weld cleaning and metal removal may be necessary to provide a surface free of undercutting, splatter, ripple, etc.

4.2.5.5 Waste Package Filler Material Testing and Development

This waste package development task will develop the means of properly emplacing waste package filler materials. This is contingent on engineering design analyses and performance analyses determining that the use of a filler material is deemed to offer a technical benefit. Engineering benefits of using filler materials have been established, such as reducing the waste package internal void space thereby limiting the quantity of water which could enter into the waste package.

The testing phase of this development task will include development of techniques for remote placement of the material, and confirmation of complete and proper placement. A secondary task of development will be measurement of any material physical properties as may be required. Material types to be investigated will include graded granular materials, cementitious materials, and low-temperature melting materials, primarily metals. The long term physical/chemical stability potential of the selected cementitious materials will also be investigated. Materials compatibility testing may also be required. Steel shot has been tested as likely filler material for spent nuclear fuel and the results of the testing program are detailed in the *Waste Package Filler Material Testing Report* (CRWMS M&O, 1996b).

The filler material development program will provide test specimens consisting of subscale and full scale mockup fabrications. The conclusion of the ACD phase testing program will lead to a formal evaluation report and drafts of proposed specifications for filler material composition, material conditioning, and material handling for filler material remote placement processes. During the VA and LAD program phase, manufacturing development will produce several sets of full scale prototype parts for final development and acceptance testing, and will provide the waste package filler material development final report and final specification package.

4.2.5.6 Remote In-service Inspection

The requirements established of the waste package, require a performance confirmation period. The objective of this development task is to select and develop remote in-service-inspection equipment and techniques that are technically and economically acceptable, and which can withstand the radiation dose and temperatures of the waste package environment. The needed equipment will consist of sensors, transmitters, and cabling to be installed in a selected area within the repository for the purpose of monitoring conditions therein. The sensors may be mounted on or around waste packages and/or sample material coupons, mounted on and within the drift rock walls both near and far from emplaced waste packages, and would also be located within any environmental monitoring stations as might be placed in the drifts. Parameters which may be expected to be of interest in order to monitor conditions within the repository will include: temperature, pressure, humidity, pH level, air velocity, strain gages, radioactivity level, and seismic acceleration.

4.3 Strategies for Achieving Disposal Criticality Control and Containment and Controlled Release

4.3.1 Strategy for Achieving Disposal Criticality Control

The strategy for disposal criticality control involves a defense-in-depth approach. The combination of the engineered barrier segment and natural system will be used to provide disposal criticality control and to ensure the containment and isolation of radionuclides. For successful license application, the design must demonstrate that the engineered and natural barriers will meet radionuclide release and disposal criticality control requirements.

A set of criticality control acceptance criteria must be developed that accounts for the combination of the waste forms and engineered barrier segment to be used for disposal in conjunction with the Natural Barrier Segment must be developed. To develop the acceptance criteria, and to demonstrate compliance with the criteria, requires the development of an NRC accepted analysis methodology. The *Disposal Criticality Analysis Methodology Topical Report* will fulfill this need.

The methodology to be outlined in the topical report will include a risk-based approach for evaluating the disposal criticality control performance of a given waste form in the engineered and natural barrier systems at Yucca Mountain. The risk-based approach accounts for both the probability of a potential criticality event occurring and the consequence if the event occurs.

The determination of consequence from a potential criticality event is integrated into the overall repository system performance assessment. Total risk determination from increased radiological release resulting from a criticality is part of the total system performance assessment and is quantified in the form of total dose to the public.

The risk-based evaluation is intended to demonstrate that the NRC long-term disposal criticality requirements in the regulation, revised according to the DOE's recommendations, will be met. The evaluation will also, through a ranking process, focus resources on making changes to the engineered barrier segment to improve the overall performance.

The evaluation to demonstrate compliance will include analyses of potential critical configurations of fissile material within the engineered barrier segment and in the natural host rock outside of the emplacement drifts. The analyses will focus on the changes the engineered barrier segment and waste forms will experience over the period of regulatory concern, regardless of the time frame involved.

The evaluation includes the following:

1. Identify the fissile material configurations which can result from natural events and processes.

2. Calculate the k_{eff} resulting from the potential configurations and implemented.

3. Evaluate the consequences for those potential configurations that result in k_{eff} above the regulatory limit. The consequences will be included in the overall performance assessment of the repository.

4. If the risk is unacceptable, the processes outlined in steps 2 and 3 will be repeated. Design modifications will be implemented where appropriate. The determination of what degree of consequence is unacceptable will be provided by regulatory-based requirements for release to the accessible environment.

4.3.2 Strategy for Achieving Containment and Controlled Release

The overall strategy for waste containment and isolation is based on a defense-in-depth approach in which the EB Segment is a key component. The first part of the strategy is to contain the wastes in waste packages for an acceptable period of time (Containment) and the second part entails ensuring that release rates are acceptably low (Controlled Release). The regulatory requirement for containment period entails providing substantially complete containment for a period of not less than 300 years, but not more than 1,000 years after permanent closure of the geologic repository. The Controlled Release Period entails controlling the release of radionuclides after the Containment period. This strategy is based on requirements outlined in section 3.7 of the EBDRD (YMP, 1994). It has been assumed that substantially complete containment will not be defined quantitatively and is documented in the CDA (Key 036, CRWMS M&O, 1995a).

The role of the Waste Package Development and Materials organizations is to design and develop the Waste Package Subsystem and provide input into the development of the Underground Facility. This will result in an Engineered Barrier Segment design which will contain wastes for the period of containment with a high degree of certainty which can be demonstrated during the licensing process. The Waste Package Subsystem's ability to contain radionuclides during the Containment period is crucial, however it is also critical to meeting Controlled Release requirements. This requires a comprehensive and multi-faceted development program as described in this document.

4.4 Probabilistic and Design Basis Evaluations

4.4.1 Probabilistic Evaluation and Design Basis Events

Probabilistic evaluation involves the estimation of the probability that an undesirable event will occur by (1) defining the various sequences of failures (or processes) that can produce the event, (2) estimating the probability of each failure (or process), and (3) combining the individual probabilities to determine the probability of each sequence that may lead to the final, undesirable event. When combined with an assessment of the consequences of the undesirable event, a determination of "risk" can be made. This assessment of probability and consequences is typically referred to as Probabilistic Risk Assessment. Both probabilistic evaluation and Probabilistic Risk Assessment are used throughout industry, particularly in the nuclear power generation, for evaluating the importance of plant systems and components, identifying component failures or failure sequences that are dominant contributors to severe accident likelihood and/or public risk, and guiding design change and maintenance decisions to minimize the probability of these failures and risks.

4.4.1.1 Support for the WP Design Process

In the Waste Package design process, probabilistic evaluation techniques are being used to evaluate design options primarily by estimating the likelihood of events or processes which lead to stressing values of environmental parameters for the waste package. For this application, the probabilistic methods are appropriate and effective analysis tools because of:

- The degree of uncertainty in many of the process models.
- The complexity and number of possible design conditions resulting from these uncertainties.
- The need to design to realistic, rather than incredible (i.e., ultra-conservative) conditions.
- The need to assess vulnerabilities in the current conceptual design and identify possible improvements.

Furthermore, probabilistic evaluations will provide a part of the basis for license application by complementing the use of deterministic methods for demonstrating that certain design requirements applicable to the WP have been met (NRC, 1995).

4.4.1.2 Support for Repository Design

Preclosure probabilistic evaluations are performed jointly with Repository Design to estimate the frequency of events such as equipment failures, natural hazards, or human errors, which may potentially have an adverse effect on the WP. Those events (or combination of events) which are considered credible (frequency $>10^{-6}$ events/year) are then designated as design basis events (DBEs) and carried forward in the design analysis process to determine the response of the WP to the event. If the DBE results in a WP failure to meet a design requirement, the consequences of the WP failure are determined (i.e., fraction of total radionuclide inventory released). Information on the consequences (if any consequences) of WP DBEs is then passed to the appropriate MGDS Repository Design organization for further evaluation to determine if the available safety systems adequately mitigate the consequences of the event so as to preclude worker or public dose limits from being exceeded. In addition, if any DBE does result in a WP failure, the WP design is reevaluated to determine if changes can be made which will preclude failure.

In summary, the DBE's are that part of the probabilistic evaluation process which pertains to pre-closure, and which is used in support of Repository Design as well as WP Design.

4.4.2 Waste Package Subsystem Design Basis Fuel

A Design Basis Fuel (DBF) must be defined that will be used to demonstrate that the waste package design(s) meet regulatory and other requirements. The DBF will be comprised of two subsets of DBFs; PWR and BWR SNF. For each fuel type, the breakdown will include a thermal/shielding DBF and criticality DBF. Each DBF will be characterized in terms of age, burnup, and initial enrichment. The definition of DBF involves choosing the values of these parameters so that they are more stressing on the WP design than some stated percent of the expected SNF deliveries to the repository. The DBF will reflect design stress with respect to thermal, shielding, and criticality requirements.

The nominal waste acceptance scenario is oldest-fuel-first (OFF)(CRWMS M&O, 1995). The implication is that each reactor will fill its allocation with the oldest fuel in its inventory. Oldest-fuel-first is a reasonable assumption for various reasons, all ultimately impacting cost. The ultimate goal of the DBF analysis is to develop a range of thermal, radiological and criticality parameters that the EB Segment design must accommodate in order to be able to uniformly accept 95% of the BWR and PWR SNF which will enter the CWRMS waste stream. If the actual waste acceptance scenario provides more stressing fuel than is predicted under the OFF scenario, the percentiles may be lower. The results of the last Waste Package DBF analysis can be found in the *Waste Package Design Basis Fuel Analysis* (CRWMS M&O, 1995).

4.5 Engineered Barrier Segment / Waste Package Subsystem Materials

The WP design effort is focused on metallic, multibarrier disposal containers for large and small multipurpose-based canisters and other canistered fuel, uncanistered spent fuel, and HLW glass canisters.

The Engineered Barrier Segment also includes the Emplacement Drift Backfill Material Subsystem Element and Invert Subsystem Element. The program for testing and modeling of these materials is described in Section 4.5.3.2. Volume III, Section 4 of the *Mined Geologic Disposal System Advanced Conceptual Design Report* (CRWMS M&O, 1996a) details the status of the Materials Selection process.

4.5.1 Material Selection

The designs listed in Table 4-4 have a common design in that they are metallic, multibarrier disposal containers. This design incorporates an outer corrosion-allowance metal barrier over an inner container made of corrosion-resistant metal. The two distinctly different materials are selected to reduce the probability that a single environment will cause rapid failure of both. The WP is being designed for emplacement in a horizontal drift located in the unsaturated zone. The corrosion-allowance barrier, which will be thicker than the corrosion-resistant barrier, is being designed to corrode slowly, thus providing the inner container protection from the potential repository environment for a prolonged service life. Selection of suitable materials, therefore, exerts a significant influence on the resistance of these containment barriers to all pertinent forms of environmentally induced degradation.

4.5.2 Materials Selection Process

The WP materials selection process operates in a parallel, iterative manner with the design activities. The selection process draws heavily on previous work performed for *Preliminary Selection Criteria for the Yucca Mountain Project Waste Package Container Material* (LLNL, 1990). The activities associated with the selection process, shown in Figure 4-1, are as follows:

- Definition of component functions, performance requirements, design requirements, and environments.
- Establishment of selection criteria and weighting factors.
- Identification of candidate materials.
- Collection of information/test data.
- Application of collected information/data to selection criteria and ranking.
- Selection and review.
- Confirmatory tests of selected materials.

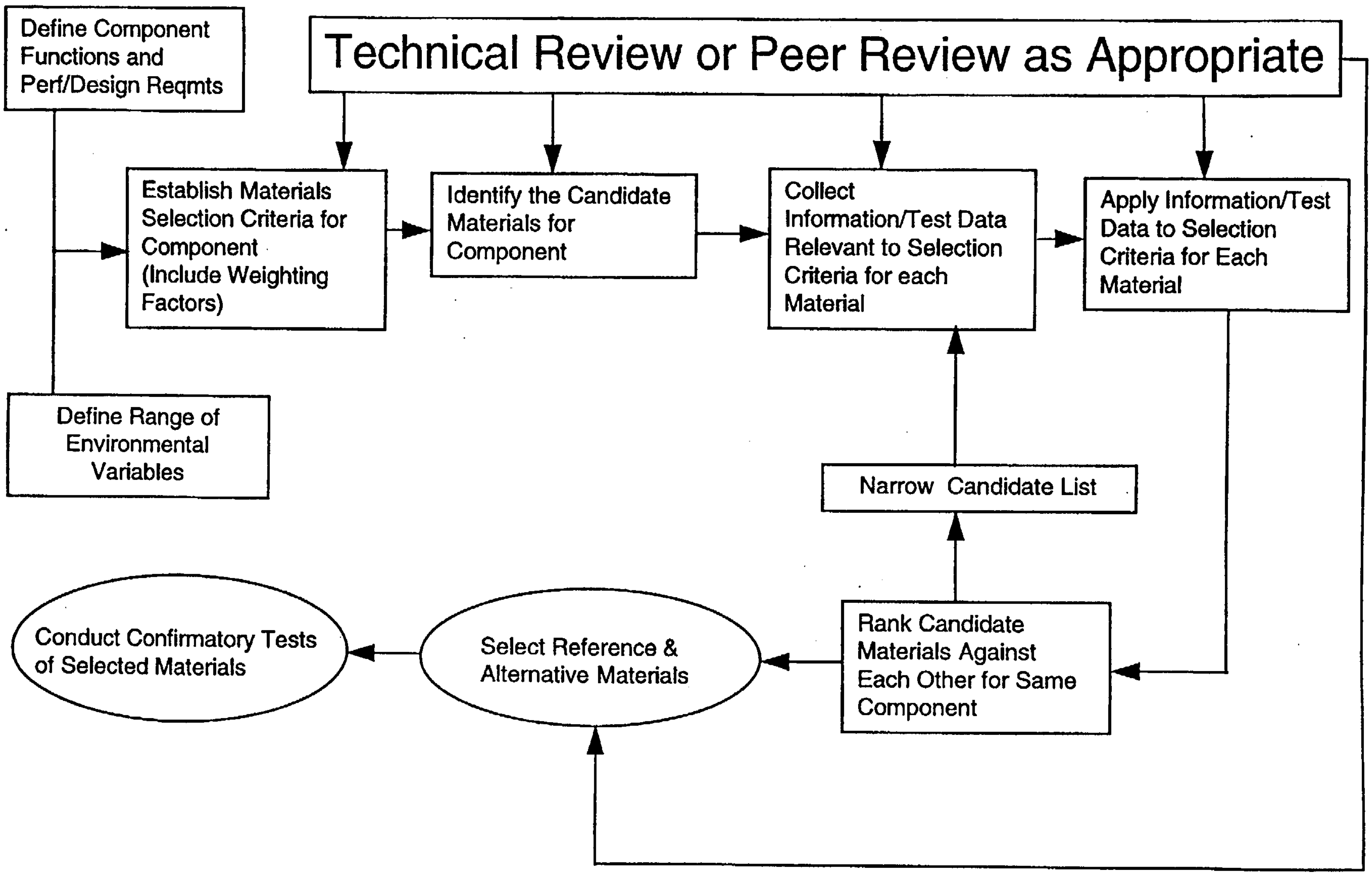

Figure 4-1 WP Material Selection Process

The criteria for barrier materials selection consider the WP design and service environment conditions. For the metallic, multibarrier designs presented, the selection criteria are essentially a composite of how a material for a specific component performs within a WP system, and how well it meets the performance and design requirements. The anticipated functions and performance and design requirements of different components of a metallic multibarrier WP have been identified, as described in Tables 4-1 through 4-7 of Volume III of the *MGDS ACD Report* (CRWMS M&O, 1996a).

The selection criteria are classified into two major categories: (1) those related to the performance of candidate materials in the anticipated repository environment, and (2) engineering-related aspects dealing with cost, engineering experience, and practical considerations of fabrication, closure, and material availability. The selection criteria under the first category may consist of several topical areas such as mechanical performance, chemical performance, predictability of performance, and compatibility with other materials. Use of the criteria in selecting barrier materials is based on engineering judgment. The selection criteria are as follows:

Performance-Related Factors

- Chemical Performance
    - Resistance to general corrosion (dry oxidation and uniform aqueous corrosion)
    - Resistance to localized corrosion (pitting and crevice)
    - Resistance to environmentally assisted cracking (stress corrosion cracking and hydrogen embrittlement)
    - Resistance to microbiologically influenced corrosion (MIC)
- Mechanical Performance
    - Strength
    - Fracture toughness (resistance to crack growth)
    - Phase stability
- Predictability of Performance
    - Existence of predictive methods to explain and predict degradation phenomena and to extrapolate existing performance data to repository time scales and conditions, or ability to develop such methods
    - Existence of long-term performance data
    - Ability to generate required data

- Acceptance for use in other nuclear applications

- Compatibility with Other Materials

  - Interactions among materials of different components
  - Interactions with waste form

Engineering-Related Factors

- Fabricability

  - Fabricability of container body
  - Ability to close and seal the container
  - Inspectability of closure
  - Postclosure damage tolerance

- Cost

- Previous Experience with the Material

  - Previous engineering experience with the material
  - Previous engineering standards for the material
  - Strategic availability of material

In a previous analysis of the *Waste Package Design (Basis for Site Characterization Plan, Chapter 8)* (YMP, 1991), engineering judgment was used to identify materials that have the desired properties and generally favorable attributes relative to the selection criteria, and container materials were selected from the candidates. A similar process will be used for the current multibarrier design. A quantitative rating will be given to each candidate material for each selection criterion. This rating will be based on available test data, the degradation mode surveys, and other relevant data in both performance-related and engineering-related categories. The weighting factor for each criterion will be multiplied by these ratings, and the results summed for each material to establish an overall material rating. These ratings will then be used to rank the candidate materials for each component. Materials will be selected for each component, followed by confirmatory testing.

4.5.3 Materials Testing

WP/EB Segment materials testing shall be conducted to provide:

a. The data base required by the modeling activity for developing and validating the material degradation mode (Performance Parameter) submodels and component behavior (Performance Measure) models. These material degradation mode submodels and component behavior models are used as the base of the model hierarchy to help demonstrate WP/EB Segment regulatory compliance.

b. The attribute data that are not already available from the literature. These data are required by the WP design activity to perform design analyses, including WP structural, criticality, and thermal analyses.

c. Confirmation that performance requirements are met by the initial selection of materials for the canistered spent fuel, uncanistered spent fuel and HLW disposal containers, and materials for the EB Segment including filler, packing and emplacement drift backfill and invert.

The technical approach to materials testing is derived directly from the performance parameters identified in Table 4-1. The performance parameters are either properties or attributes of the EB Segment components that are needed to evaluate EB Segment component performance in accordance with the performance measures.

4.5.3.1 Metal Barriers

It is very likely that metal barriers will be used to contain the radionuclides within the WP. The metallic container component and corresponding performance parameters that need to be measured (and modeled) were identified in the EB Segment technical approach (Table 4-1). The performance parameters from Table 4-1 that are associated with this component have been listed in Table 4-5 along with the appropriate tests that will lead to the determination of each performance parameter. There has been no attempt to prioritize these tests or to identify the environmental variables and their ranges that need to be investigated. As WP environment information is developed, this knowledge will be incorporated into SIPs in the form of specific environmental scenarios including parameters and ranges. The intent is to develop an understanding, to the extent possible, of each performance parameter's dependence on the WP environment.

The metallic container materials that are to be studied as part of the WP development effort have been categorized in accordance with corrosion characteristics; Metals and alloys characterized as being corrosion-resistant or corrosion-allowance. The list of candidate container materials has been narrowed and materials will continue to be investigated through the VA phase. Also, iron-base and copper-base alloys will be evaluated as potential corrosion allowance container materials.

The grain structure and metallurgical phases within the grains, including precipitates that may be in grains or along grain boundaries, will be characterized for each candidate metallic container material in the as-fabricated condition. Characterization includes the metallurgical structure and precipitates in the base material, in welds, and in the regions near the welds that may have been affected by heat from the welding process (heat-affected zones). The stability of this as-fabricated metallurgical structure needs to be understood as a function of time and temperature. The performance parameter "Phase Transformations" encompasses the characterization of metallurgical phase and precipitate behavior for each candidate material as a function of time and temperature, sufficient to provide a basis for predictive model development.

Low-temperature oxidation of metallic container materials at temperatures from above the boiling point of water to 250°C will probably be the dominant degradation mode of containers in this temperature range. Chemical affinity of metals for oxygen in a vapor or non-condensing environment as a function of humidity, results in the formation of metallic oxides which remain on the surface as a film. In some cases, the oxide film is very adherent and protective in nature, inhibiting further oxidation of the underlying metal by limiting oxygen access to the metal substrate. In other cases, the oxide film is less adherent and non-protective in nature thus allowing continuing access of oxygen to the metal and continued oxidation.

Below the boiling point of water, water films can form on the container surfaces at high relative humidities leading to aqueous corrosion. General aqueous corrosion will probably be the dominant degradation mode of corrosion-allowance container materials in contact with water. General aqueous corrosion will be active for corrosion resistant materials also, although its importance is much less for these materials due to the very adherent, protective (passivating) nature of their corrosion product films which result in extremely low rates of general corrosion. Waste Package designs may incorporate a corrosion-resistant material weld clad onto a corrosion-allowance material. In this case, the corrosion-allowance material may galvanically protect the corrosion-resistant material from attack. This effect will be investigated as part of the general aqueous corrosion testing.

Microbiologically influenced corrosion (MIC) is a form of localized corrosion which is induced by local-action cells in an aqueous environment that are created by the accumulation of microbes or microbe by-products on the surface of a metal. If it can be demonstrated that a particular candidate metal is not susceptible to this form of corrosion or that the rates associated with other forms of localized corrosion are higher than MIC, then decreased emphasis can be placed on fully characterizing and modeling MIC.

Pitting (and crevice corrosion) of metals occurs in aqueous environments. The rate of pit growth is rapid relative to general corrosion rates. If the corrosion product film is not passivating in nature, such as with corrosion-allowance materials, then the tendency to degrade by pitting is dominated by general aqueous corrosion processes, and general corrosion will prevail over a broad range of environmental parameters.

The performance parameters of interest in modeling pitting corrosion behavior are:

- E_{crit} - Electrochemical potential above which pitting will initiate on the surface of the metal
- E_{prot} - Electrochemical potential below which a propagating pit will stop growing
- E_{corr} - Open circuit (no applied potential) electrochemical potential that exists on the surface of a metal in an aqueous environment in its freely corroding state
- Pit Penetration Rate - The rate of penetration of a pit into the metal.

Table 4-5 Metal Barriers Testing Program Summary

Component	Performance Parameter	Test
Metallic Container	Phase Transformation	Aging/Metallographic
	Oxidation Rates	Air/Steam
	General Corrosion Rates	Aqueous Bath
	Microbiologically Influenced Corrosion (MIC) Rates	Aqueous Bath
	E_{crit} for Pitting	Potentiodynamic
	E_{prot} for Pitting	Potentiodynamic and Aqueous Bath
	Crevice Corrosion Rates	Potentiostatic and Aqueous Bath
	Pit Penetration Rates	Potentiostatic
	Crack Propagation Rates	Constant/Cyclic Load
	Threshold Stress Intensity Factors	Cyclic Load
	Tensile Properties	Tension
	Creep Properties	Creep (uniaxial)
	Fracture Toughness	J-Integral Fracture

To develop these pitting performance parameters, potentiodynamic scanning as well as potentiostatic/pit depth tests will be required to understand the mechanisms, initiation behavior and rates of pitting corrosion to support predictive model development. Immersion tests shall be performed on each candidate container material to understand the initiation and propagation rates of localized corrosion in crevices and, if possible, to demonstrate that localized corrosion rates in crevices are bounded by pitting corrosion rates. This would minimize the amount of work required to understand crevice corrosion behavior.

Environmentally-assisted (stress corrosion) cracking is a degradation mode that occurs by the synergistic interaction of mechanical stress and corrosion processes in that component. Simultaneous exposure to these factors leads to very rapid propagation of cracks, far in excess of that which would occur by stress acting alone.

The performance parameters of interest in modeling environmentally assisted cracking behavior are:

- Crack Propagation Rates - Crack penetration rate as a function of time, stress, and other environmental factors such as temperature and water composition

- Threshold Stress Intensity Factors - Stress intensity factor below which the crack propagation rate approaches zero. This needs to be established as a function of all important environmental factors.

The mechanical instability of candidate container materials is associated with the application of a mechanical stress to the component in the absence of chemical effects. Deformation and failure occur differently depending on the metal and its processing and fabrication history.

The performance parameters or attributes of interest in modeling mechanical instability behavior are:

- Tensile Properties - Modulus of Elasticity, Proportional Elastic Limit, Yield Strength, Ultimate Tensile Strength, Poisson's Ratio, Uniform Elongation, Total Elongation, Reduction of Area

- Creep Properties - Deformation (strain) as a function of stress and time

- Fracture Toughness - The ability of a material, with a crack, to absorb energy.

To determine these performance parameters, appropriate testing of each candidate material will be required to understand the mechanical behavior as a function of temperature and strain rate.

4.5.3.2 Other Engineered Barrier Materials

The program for the evaluation of other engineered barrier materials has just been initiated. Other Engineered Barrier Materials include potential backfill, packing, and invert materials, as well as materials for drip shields. The near-term objective of the effort is to characterize potential engineered materials versus their function in the system. The evaluation will determine the benefits and detriments of these materials to system performance and develop a short list of materials to further characterize and recommend as a design element. Work within the WP program and various systems studies are being integrated to assure efficient use of resources. The WP effort has focused on the chemical interactions of engineered barrier materials with the WP components, while the system study portion has examined the retardation and release of radionuclides from the Engineered Barrier Segment using the Yucca Mountain Integrating Model code. Longer-term WP work will include appropriate property determinations of the potential materials, engineered barrier/waste package material interactions, including corrosion products and colloids, utilizing the EQ3/6 code, and the development of predictive models.

The backfill functions and performance parameters are identified in the EB Segment technical approach (Table 4-1). Performance parameters associated with the backfill and invert are listed in Table 4-6 along with the appropriate tests that will lead to the determination of each performance parameter. There has been no attempt to prioritize these tests or to identify the environmental variables and their ranges that need to be investigated. As WP environment information is developed, this knowledge will be incorporated into SIPs in the form of specific, environmental scenarios including parameters and ranges. The intent is to develop an adequate understanding of each performance parameter's response to the repository environment.

Table 4-6 Backfill and Invert Testing Program Summary

Component	Performance Parameter	Test
Emplacement Drift Backfill and Invert	Material Compatibility Backfill Compaction Permeability of Air in Backfill Hydraulic Conductivity of Water in Backfill Thermal Conductivity of Backfill Components	Corrosion Testing/Simulation Relative Density Permeability Hydraulic Conductivity Thermal Conductivity

4.5.3.3 Integrated Testing

The objectives of this effort are to determine the transport properties of radionuclides in the EB Segment and near field and to develop and validate a model to describe the rate of release of radionuclides from the near field. Data from the experimental programs including those shown in Table 4-7 will be utilized to model the radionuclide release from the EB Segment.

The transport of radionuclides, either in solution or as colloids, through the corrosion products which exist on the surface of the base metal and any potential invert, is a diffusion process. The diffusion of radionuclides through these materials is important in understanding release rates of radionuclides from the containers. The performance parameters of "Diffusion Coefficients of Radionuclides" will provide the diffusion characteristics needed to assess this aspect of radionuclide transport.

The transport of radionuclides through cracks which exist in the base metal when breach of a container occurs by a cracking mode (environmentally assisted cracking) is in part a diffusion process and is important in understanding release rates of radionuclides from the containers. The performance parameter of "Diffusion Coefficients of Radionuclides in Water" will provide the diffusion characteristics needed to help assess this aspect of radionuclide transport. Also needed for this purpose is the "Crack Geometry." Knowledge of the likely crack geometries (and effective hydraulic conductivity of a breached container) along with the radionuclide diffusion coefficients in water will allow calculation of radionuclide transport through cracks. The diffusion and the potential retardation of radionuclides through the potential packing and invert materials must also be evaluated.

Table 4-7 Integrated Testing Program Summary*

Component	Performance Parameter	Test
Emplacement Backfill/ Invert	Diffusion Coefficients of radionuclides (RNs) in Air	Gaseous Diffusion
Emplacement Backfill/ Invert	Diffusion Coefficients of RNs in Water	Aqueous Diffusion
Emplacement Backfill/ Invert	Retardation Coefficients	TBD
Metal & Non-Metal Barriers	Diffusion Coefficients of RNs in Corrosion Prod.	Solid Diffusion
Metal & Non-Metal Barriers	Diffusion Coefficients of RNs in Water	Aqueous Diffusion
Metal & Non-Metal Barriers	Crack Geometry (Effective Hydraulic Conductivity)	Hydraulic Conductivity

*Some of the backfill tests may be performed under the EB Segment Field Test Program.

4.5.3.4 Non-Metallic Barriers

Non-metallic barriers may be used to contain the radionuclides within the WP either as monoliths or thermally-sprayed coatings. It is expected that the non-metallic materials will provide the increased degree of radionuclide isolation identified in 10 CFR 60.21(c)(1)(ii)(D) dealing with the consideration of alternative designs and barriers. The non-metallic container component and corresponding performance parameters that need to be measured (and modeled) were identified in the EB Segment technical approach (Table 4-1). The performance parameters from Table 4-1 that are associated with these components are listed in Table 4-8 along with the appropriate tests that will lead to the determination of each performance parameter. There has been no attempt to prioritize these tests or to identify the environmental variables and their ranges that need to be investigated.

As WP environment information is developed, this knowledge will be incorporated into SIPs in the form of specific environmental scenarios including parameters and ranges. The intent is to develop an understanding, to the extent practicable, of each performance parameter's dependence on the WP environment, so that a judgment can be made during VA as to whether the alternative approach should be further explored.

The non-metallic materials being considered include oxides, such as alumina, titania, and alumina-silica combinations, as well as non-oxides, such as graphite, carbides, and nitrides. Early in the program, screening studies will be performed to narrow the candidate list, followed by sub-scale fabrication of components.

Table 4-8 Non-Metallic Barriers Testing Program Summary

Component	Performance Parameter	Test
Non-Metallic Container	Dissolution Rates	Leach/Dissolution
	Tensile Properties	Tension
	Creep Properties	Creep (uniaxial)
	Fracture Toughness	J-Integral Fracture
	Crack Propagation Rates	Static/Cyclic Load
	Threshold Stress Intensity Factors	Static/Cyclic Load
	Diffusion Coefficients of RNs in Water	Aqueous Diffusion
	Diffusion Coefficient of C-14 Dioxide in Non-Metallic Materials	Solid Diffusion

Development of barrier concepts in this material category has recently been curtailed because of funding limits. This class of materials have many superior properties which should be investigated. The important properties for this class of materials are the mechanical properties (particularly fracture toughness), permeability, and dissolution resistance. Fracture via delayed crack propagation under stress is believed to be a more limiting property of these ceramic materials than is permeability or dissolution resistance. There are two potential fracture sources to consider, pre-existing defects at the time of emplacement and defects formed after emplacement. These sources will be influenced by the fabrication and closure methods. The testing will emphasize fracture toughness determination. Fiber reinforcement can be utilized to improve the fracture toughness of these materials; however, the permeability of the resulting composite to gases and liquids is higher than for pure ceramics.

4.6 Waste Form Testing and Modeling

The objective of these activities is to generate waste form dissolution data for use in performance assessments and for direct use in licensing.

There are two types of waste forms to be disposed of in a deep geologic repository: SNF and HLW glass. Each of these waste forms consists of two "components" for which functions, performance measures, and performance parameters have been assigned. In the case of SNF, the components are spent fuel pellets and cladding. For the HLW glass, the components are the HLW glass itself and the metallic pour canister. These components and the corresponding performance parameters that need to be measured (and modeled) were identified in the EB Segment technical approach (Table 4-1). The performance parameters associated with the four waste form components from Table 4-1 have been consolidated and grouped in Table 4-9.

Tests are identified in Table 4-9 that will lead to the determination of each performance parameter. There has been no attempt to prioritize these tests or to identify the environmental variables and their ranges that need to be investigated. As WP environment information is developed, this knowledge will be incorporated into SIPs in the form of specific, environmental scenarios including parameters and ranges. The intent is to develop an understanding, to the extent possible, of each performance parameter's dependence on the WP environment.

Cladding

The key SNF cladding performance parameters are:

- Oxidation Rates
- General Corrosion Rates
- Pit Penetration Rates
- Pit Initiation Rates
- Creep Rupture Properties (includes hydride effects).

These spent fuel cladding performance parameters (listed in Table 4-9) are sensitive to temperature, water flow rate and composition, Eh, pH, and mechanical stress in the cladding. The performance parameter response to these environmental variables is affected by variations in cladding alloy chemistry, thermomechanical history during fabrication, in-reactor environment history, as well as post-discharge thermal and mechanical loading histories.

Table 4-9 Waste Form Testing Program Summary

Component	Performance Parameter	Test
SNF Cladding	Oxidation Rates General Corrosion Rates Pit Penetration Rates Pit Initiation Rates Creep Rupture Properties (includes hydrid formation effects)	Air/Steam Aqueous Bath Potentiostatic Potentiostatic Creep
Spent Fuel Pellets	Amount of Carbon-14 Released as a Gas Radionuclide Concentrations in Contacting Water	Inventory Measurements, C-14(CO_2) Diffusion Dissolution oxidation
HLW Glass Canister	Grain Boundary Sensitization Environmentally Assisted Cracking Oxidation Rates General Corrosion Rates Pit Penetration Rates Crevice Corrosion Rates	Time/Temp Exposures Crack Propagation Air/Steam Aqueous Bath Potentiostatic Potentiostatic
HLW Glass	Radionuclide Concentrations in Contracting Water	Dissolution Air/Steam

Because of the many anticipated historical and environmental dependencies of spent fuel cladding performance, the intent of the spent fuel cladding testing effort is to determine the conservative bounds of the performance parameters. This will require testing the particular cladding that according to engineering judgement will respond most rapidly to the environmental conditions of the test. In some cases, scoping tests will be needed to identify conservatively bounding environmental conditions.

Spent Fuel Pellets

The key spent fuel pellet performance parameters are:

- Amount of Carbon-14 Released as a Gas
- Radionuclide Concentrations in Contacting Water.

These spent fuel pellet performance parameters are sensitive to temperature, water flow rate and chemistry, Eh, and pH. The amount of Carbon-14 released as a gas can be related conservatively to the Carbon-14 inventory in the fuel-cladding gap, the spent fuel grain boundaries, and the UO_2 matrix. Therefore, determination of these inventories by a combination of measurements and calculation is needed.

An understanding of the radionuclide concentrations in repository water flux is an important step in calculating radionuclide release. A knowledge of radionuclide inventory and spent fuel dissolution rate will provide the necessary basis for determining radionuclide concentrations. Thus, it is important that spent fuel dissolution behavior be investigated. The release of radionuclides is directly affected by the spent fuel pellet surface area available for dissolution. Therefore, spent fuel oxidation tests are needed because the oxidation state influences the surface area available to the groundwater for dissolution. Spent fuel burn up and fission gas release are also key variables that need to be incorporated into the spent fuel performance testing effort.

HLW Glass Canister

The key HLW glass canister (anticipated to be American Iron and Steel Institute Type 304L stainless steel) performance parameters are:

- Grain Boundary Sensitization
- Environmentally-Assisted Cracking
- Oxidation Rates
- General Corrosion Rates
- Pit Penetration Rates
- Crevice Corrosion Rates

These stainless steel canister performance parameters (also listed in Table 4-1) are sensitive to temperature, water flow rate and composition, Eh, and pH.

In addition, due to the long storage period and the potential that the Type 304L canisters would become sensitized and attacked by environmentally-assisted cracking, no credit is currently assumed for this barrier and no tests are planned.

HLW Glass

The key HLW glass performance parameter is:

- Radionuclide Concentrations in Contacting Water.

Borosilicate glass performance is sensitive to temperature, water flow rate and composition, Eh, and pH. An understanding of the radionuclide concentrations in effluent water is important for use in calculating radionuclide release. The understanding of radionuclide inventory and glass dissolution rate will provide the necessary basis for determining radionuclide concentrations. Thus, it is important that HLW glass dissolution behavior be investigated. An understanding of the glass dissolution behavior both with and without prior exposure to an air-steam environment is needed.

4.7 Model Development

The hierarchal framework for model development requires the development of performance parameter submodels, such as WP containment breach (and breach rate) and waste form release. These model hierarchies, which are tied to issue resolution, are shown in Figures 4-2 and 4-3.

The goal of this effort is the development of detailed mechanistic models that adequately describe each degradation and release mode identified in Figures 4-2 and 4-3, as well as the other portions of the system that need to be modeled. Using the inputs described above, conceptual models will first be developed. These will be supported by the testing program which includes mechanism characterization, service condition determination, and accelerated tests. The models will be enhanced as results from these test programs become available. Performance predictions can then be made that can be tested using confirmation tests.

The models will, to the extent possible, include the variability of the material being degraded. If complete mechanistic understanding cannot be obtained, then partial understanding will be sought. This follows the approach given in ASTM C 1174-91, described in Subsection 4.1. Lastly, if neither full nor partial mechanistic understanding is possible, then bounding models will be utilized. Validation will be performed for each model developed. It is worth noting that total validation in the classic sense is not achievable given the time frame of repository performance. However, partial validation may be possible with the aid of natural analogues, both for the corrosion-allowance WP materials and the waste forms. Long-term (several years to several decades) and in situ testing can also add confidence that the degradation modes are understood.

This model development approach is shown schematically in Figure 4-4. The approach shows the parallel nature of the model development and the testing efforts. Model and test plan development are closely coupled. Results from the early tests strongly impact the evaluation of the conceptual model, while results from confirmation tests and long-term tests impact the final model. Model validation involves both the long-term test results and information from appropriate natural analogues.

The degree of detail provided in each of the submodels will vary depending on the contribution that each is expected to make to the degradation process. For example, the degradation of the corrosion allowance materials due to a localized corrosion process is expected to be small. Thus, the submodel that describes this process can be bounding, rather than totally mechanistic. This assumption, of course, will be confirmed as an outcome of testing or degradation mode surveys. A similar approach will also be taken for waste form release, for example, for the release of radionuclides from hardware.

The submodels developed for each degradation mode must be adapted for system application, as shown in Figure 4-4. This implies that the system model must be less complex and be bounding of the results predicted by the more detailed submodels. However, the parametric dependencies provided in the submodels must be retained in the system models, and the overall predictions must also be retained.

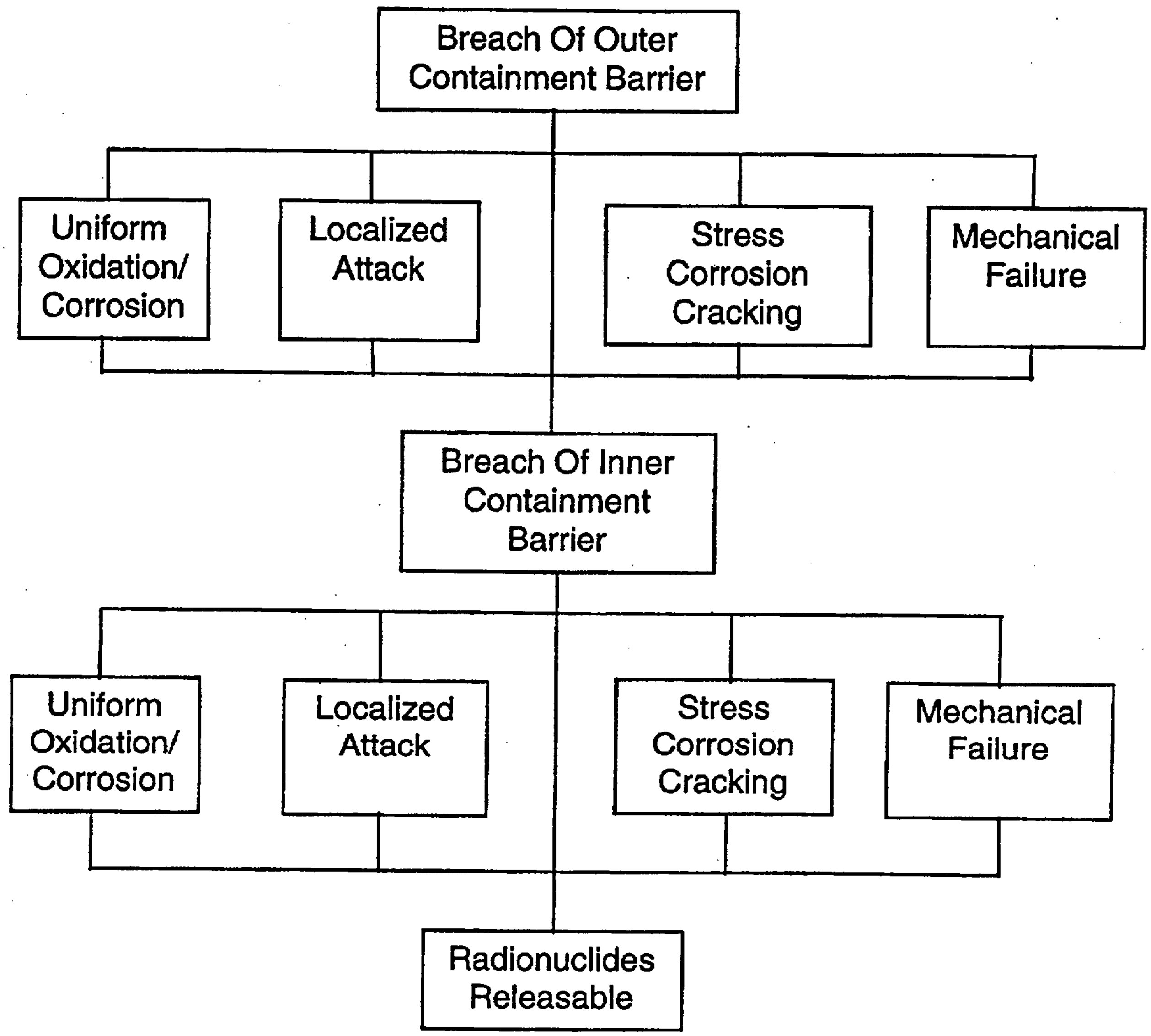

Figure 4-2 Waste Form Release Model Hierarchy

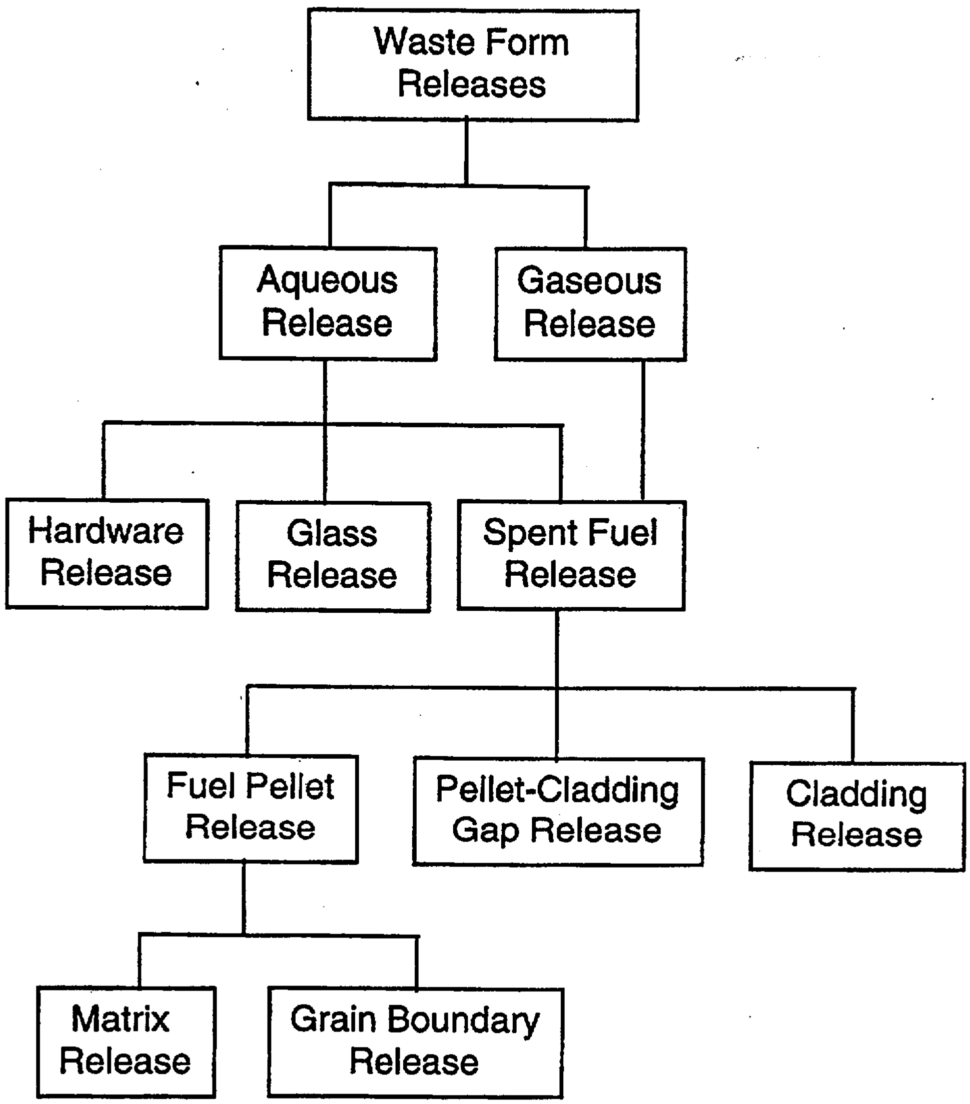

Figure 4-3 Waste Form Release Model Hierarchy

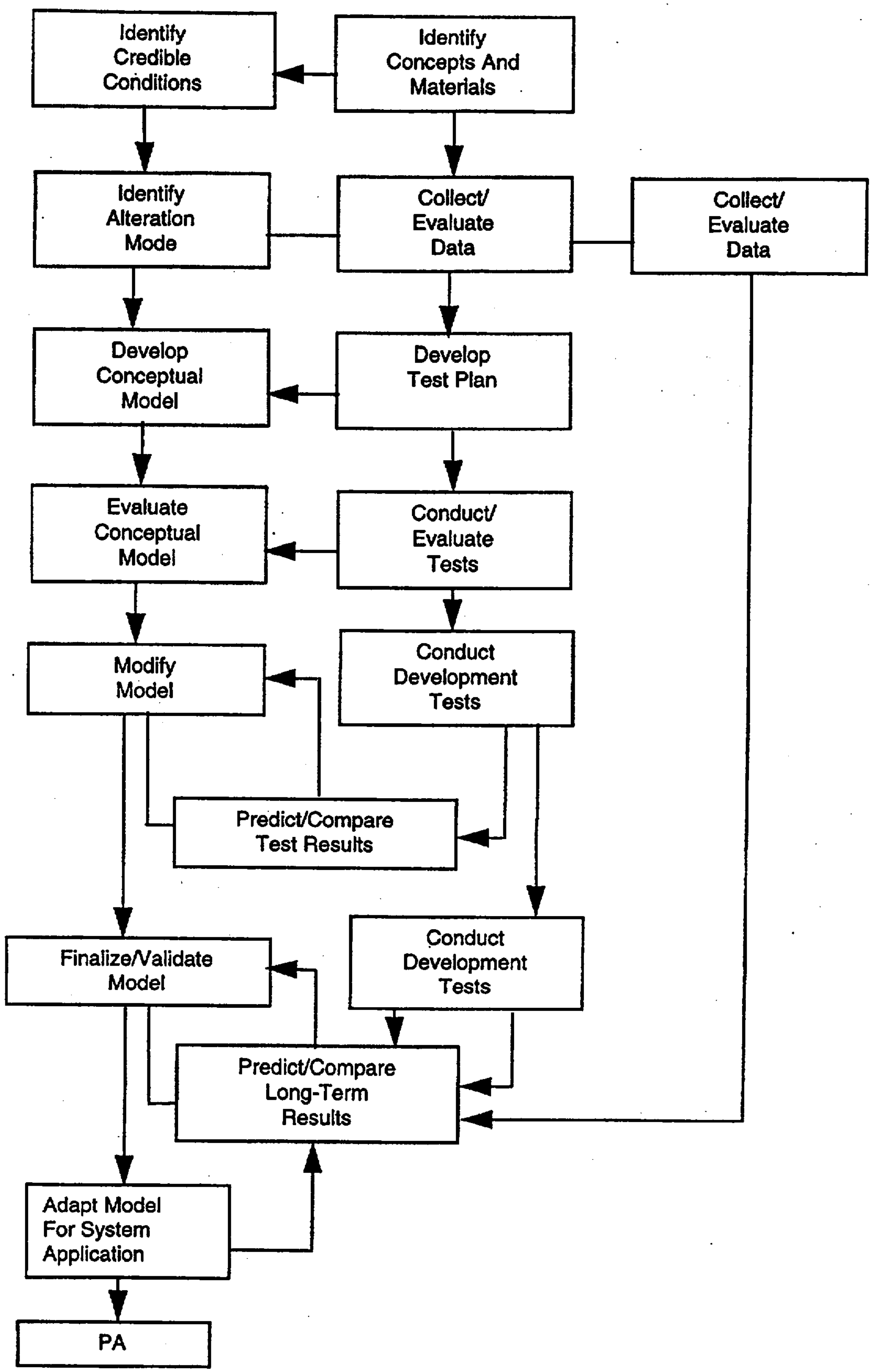

Figure 4-4 Model Developement Process Chart

5. WASTE PACKAGE SUBSYSTEM INTEGRATION

Integration of the Waste Package Subsystem with the Engineered Barrier Segment and other segments of the MGDS Element will occur by two means. A fully integrated repository design will be developed through a systems design approach and by the integrated planning of design activities in the Viability Assessment and License Application phases. The outcome of Integrated Planning will be detailed in the Revised Program Plan.

In addition to design integration, testing and science programs will be coordinated to insure full integration with Waste Package Development.

5.1 Requirements Development and Analysis

Performance requirements establish what the architecture (Structures Systems and Components (SSCs) and geologic setting) must be capable of accomplishing, how well they must perform in quantitative, measurable terms, and the environments in which they must operate. The development of operational and specialty engineering requirements are integrated as part of the requirements development process. These requirements are captured in the EBDRD and will be incorporated in Systems Description Documents (SDDs) for the SSCs. These performance requirements will be compared against the Advanced Conceptual Design and Waste Isolation Strategy to ensure that all key performance requirements are being met.

Integrated Product Teams (IPTs) with representation from all areas (i.e. design, scientific programs, performance assessment, and systems engineering) within the M&O are utilized to develop the primary requirements for the SSCs. The utilization of IPTs is a key integration tool in MGDS development. The first step in the requirements development is the determination of the functions required to satisfy the upper level requirements based on the current conceptual design and concept of operations. As the functions are identified, they are defined and documented in the *MGDS Functional Analysis Document* (CRWMS M&O, 1996). Performance and operational attributes and requirements are then developed by the IPT for each function. The performance requirements are based on performance assessment sensitivity studies, MGDS systems studies or are derived from higher level requirements and experience.

This process is conducted in an iterative manner with the development of engineering design and formulation of scientific solutions. After an architectural or scientific solution has been selected, lower level functions and requirements are developed. This iterative approach allows the design of the overall system to precede in a logical and controlled manner. As the process iterates, the participation in the IPTs is modified to reflect the areas being analyzed further. The successive iterations are based on the requirements and functions captured in the SDDs, the operational descriptions and the current architectural/scientific solution.

5.2 Materials Testing Activities

Metal barrier testing that will be performed by the Waste Package Materials organization is described in the Lawrence Livermore National Laboratories (LLNL) SIP for Metal Barrier Selection and Testing. Glass and spent fuel waste form testing that will be performed is described in the LLNL

SIPs on Glass Waste Form Testing and Spent Fuel Waste Form Testing. Integrated testing is described in the SIP on Integrated Testing. Since funding for this activity has been reduced, testing to be performed will be described in the annual plans.

Integration of the results of these activities is performed by the M&O. The prioritization of the activities to be performed in any fiscal year will be recommended by the M&O as part of the annual development of the budget.

5.3 Performance Assessment Activities

The activities performed under model development generally are separated into research and engineering activities. Currently, the work that requires the development of a mechanistic understanding of container materials and waste forms is within the scope of the national laboratories effort. These models are the base of the performance assessment hierarchy pyramid. The intermediate and upper levels of the pyramid are the subsystem and system models, including the development of a WP performance model that interfaces between the mechanistic models and the system models.

Metal barrier performance modeling that will be performed by the Waste Package Materials organization is described in the LLNL SIP for Metal Barrier Selection and Testing. Integration of the results of these activities is performed by the M&O. Parametric and validation testing that supports model development will be performed as described in Subsection 5.2. Glass and spent fuel waste form behavior modeling that will be performed by the Waste Package Materials organization is described in the LLNL SIPs on Glass Waste Form Testing and Spent Fuel Waste Form Testing. Integration of the results of these activities is performed by the M&O. Parametric and validation testing that supports the model development will be performed by as described in Subsection 5.2.

Performance analysis activities performed by the M&O include the exercise of the available WP codes to evaluate the design options under development. This activity will also identify testing and modeling needed to support the design effort.

The prioritization of the activities to be performed in any fiscal year will be recommended by the M&O, as part of the annual development of the budget. These recommendations will then be submitted to the Yucca Mountain Site Characterization Office for review and approval.

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APPENDIX
Waste Package Development QAP-2-0 Evaluations

TITLE	Document Identifier
Engineering Development	BB0000000-01717-2200-00001
MPC Design Compatibility with the MGDS	BB0000000-01717-2200-00003
Analyze Material and Performance Information and Data in Support of WP/EBS	BB0000000-01717-2200-00004
Waste Package/Engineered Barrier Segment Materials Selection	BB0000000-01717-2200-00005
Prepare Status Reports and Other Documents and Reports Used for Information Only	BB0000000-01717-2200-00006
Develop Technical Documents	BB0000000-01717-2200-00007
Develop Technical Documents For Informational Purposes	BB0000000-01717-2200-00008
Formal Review of Technical Documents	BB0000000-01717-2200-00009
Informal Review of Technical Documents	BB0000000-01717-2200-00010
Prepare, Review, Transmit, and/or Present Reports, Presentations, Interoffice	BB0000000-01717-2200-00011
Compile and Summarize Background Information and Data	BB0000000-01717-2200-00012
Develop Engineering and Scientific Software	BB0000000-01717-2200-00013
MGDS Inputs to the MPC System Design Procurement Specification TBVs	BB0000000-01717-2200-00014
Qualification of Acquired Engineering and Scientific Software	BB0000000-01717-2200-00015
Verification and Validation of Developed Engineering and Scientific Software	BB0000000-01717-2200-00016
Coordination, Preparation and Review of the Waste Package Conceptual Design Report	BB0000000-01717-2200-00017
Determine Data and Modeling Needs for Waste Package/Engineered Barrier Segment	BB0000000-01717-2200-00019
Waste Package/Engineered Barrier Segment Component and Performance Requirements	BB0000000-01717-2200-00020
Formal Review of Design Requirements	BB0000000-01717-2200-00021
Environment, Waste Forms, and Materials Inputs	BB0000000-01717-2200-00022
Perform Criticality, Thermal, Structural, and Shielding Analyses	BB0000000-01717-2200-00025
Perform Criticality, Thermal, Structural, and Shielding Scoping Analyses	BB0000000-01717-2200-00026
Prepare Drawings of Waste Package/Engineered Barrier Segment Configuration Items	BB0000000-01717-2200-00027
Prepare Figures and/or Sketches Which Illustrate Design Configurations	BB0000000-01717-2200-00028
Perform Waste Stream Analysis to Determine Design Basis Fuel	BB0000000-01717-2200-00029
Perform Probabilistic Waste Package Design Analyses	BB0000000-01717-2200-00030
Perform Probabilistic Waste Package Concept Scoping Analyses	BB0000000-01717-2200-00031
Prepare the Disposal Criticality Analysis Technical Report	BB0000000-01717-2200-00032
QARD-Required Support of Other Activities	BB0000000-01717-2200-00034
Studies Not Supported by the Office of Civilian Radioactive Waste Management	BB0000000-01717-2200-00035