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Engineered Barrier System and Waste Package Design Concepts for a Potential Geologic Repository at Yucca Mountain

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Abstract

We are using an iterative process to develop preliminary concept descriptions for the Engineered Barrier System and waste-package components for the potential geologic repository at Yucca Mountain. The process allows multiple design concepts to be developed subject to major constraints, requirements, and assumptions. Involved in the highly interactive and interdependent steps of the process are technical specialists in engineering, metallic and nonmetallic materials, chemistry, geomechanics, hydrology, and geochemistry. We have developed preliminary design concepts that satisfy both technical and nontechnical (e.g., programmatic or policy) requirements.

Introduction

We are using an integrated, interactive process to generate preliminary design concepts for an Engineered Barrier System (EBS) at Yucca Mountain. This process involves functional-analysis techniques to identify the functions and mission requirements of the EBS, and an iterative systems-engineering process to synthesize descriptions of preliminary design concepts.

Finalization of promising concepts must await data that can only be obtained from underground access to the proposed repository horizon at Yucca Mountain; we expect that this horizon will be opened in 1996.[1] Until that time, we will use a systems-engineering process to study two or more conceptual design configurations. We will also develop prototypes, as needed, to demonstrate feasibility of the concepts.

In this paper, we:

- Provide some background to our conceptual-design efforts.
- Describe our conceptual-design process and several preliminary concepts resulting from the process.
- Discuss the ranking and selection process we will use to evaluate alternative concepts.

Background

The Nuclear Waste Policy Act (NWPA) of 1982 created an Office of Civilian Radioactive Waste Management (OCRWM) within DOE with the responsibility for siting, constructing, and operating a repository for spent nuclear fuel and high-level radioactive waste (HLW). Pursuant to the Act, 40 CFR 191 gave the U.S. Environmental Protection Agency (EPA) the responsibility for developing standards to protect the environment from offsite releases of radioactive material from a repository, and 10 CFR 60 gave the U.S. Nuclear Regulatory Commission (NRC) responsibility for announcing the technical requirements necessary to license all phases of repository operation. In 1987, Congress amended the NWPA to focus site-characterization efforts on a site at Yucca Mountain in Nevada.

The NWPA and 10 CFR 60 mandate that radioactive materials placed in the repository be contained within an engineered barrier system (EBS). As defined by 10 CFR 60, an EBS comprises waste packages stored within an underground facility. A waste package is defined as the

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"waste form and any container, shielding, packing, and other absorbent materials immediately surrounding an individual waste container." An underground facility is defined as "the underground structure, including openings and backfill materials, but excluding shafts, boreholes, and their seals."

DOE has responded to the requirements of the NWPA and related CFRs by drawing up and issuing its *Waste Package Plan*,[2] which provides a framework for the design and implementation of an EBS at Yucca Mountain that can be shown in an NRC licensing proceeding to meet all applicable statutory and regulatory requirements. All design studies conducted under the Plan are to be carried out in accordance with the Management Systems Improvement Strategy (MSIS), issued by the Director of OCRWM in August 1990, which calls for a rigorous implementation of systems engineering principles with a special emphasis on functional analysis.

The studies reported in this paper represent a preliminary conceptual-design effort conducted under the earliest phase of the *Waste Package Plan*.

Conceptual-Design Studies

Our conceptual-design studies involve functional analysis combined with an iterative systems-engineering process.[3,4] In this section, we describe:

- Functional Analysis and Mission Requirements
- Concept Synthesis
- Preliminary Concepts
- Requirements Documents

Functional Analysis and Mission Requirements

The functional-analysis approach establishes a framework for integrating program-management efforts with technical-requirements analyses to create a unified, consistent program. This approach recognizes that, just as the facilities and equipment comprising the physical waste-management system must perform certain functions, so the program-management systems must perform certain functions to successfully bring the physical system into being.

We performed a top-down functional analysis to identify the EBS functions and to establish the EBS mission requirements. The breakdown of the functions into the first four levels is shown in Fig. 1. This functional analysis started with the top need, Manage Waste Disposal, and flowed down through Dispose of Waste into three major functions, each containing elements for the EBS due to interface relationships. Fourth-level functions include Handle Waste, Contain Waste, Limit Release of Radionuclides, Confirm Performance, Assess Performance, and Monitor Performance. The geologic repository interfaces for the EBS include the EBS to the subsurface operations area, the EBS to the Natural Barrier System (NBS), the EBS to the surface operations area, and the internal Waste Package interface with the underground facility. These interfaces and the boundaries are shown in Fig. 2.

By decomposing the waste-management system, we were able to define the EBS mission requirements so that the mission statement contained the objectives and addressed environments, constraints, and measures of effectiveness. The EBS mission is illustrated in Fig. 3. In doing this analysis, we focused on the major constraint that the EBS must be designed using a multibarrier

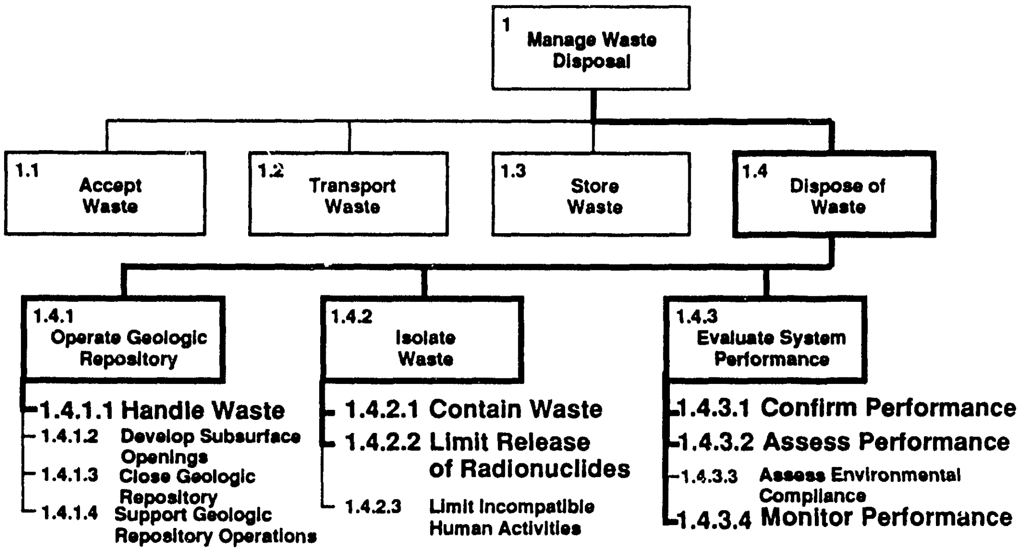


Figure 1. Related functions for the Engineered Barrier System.

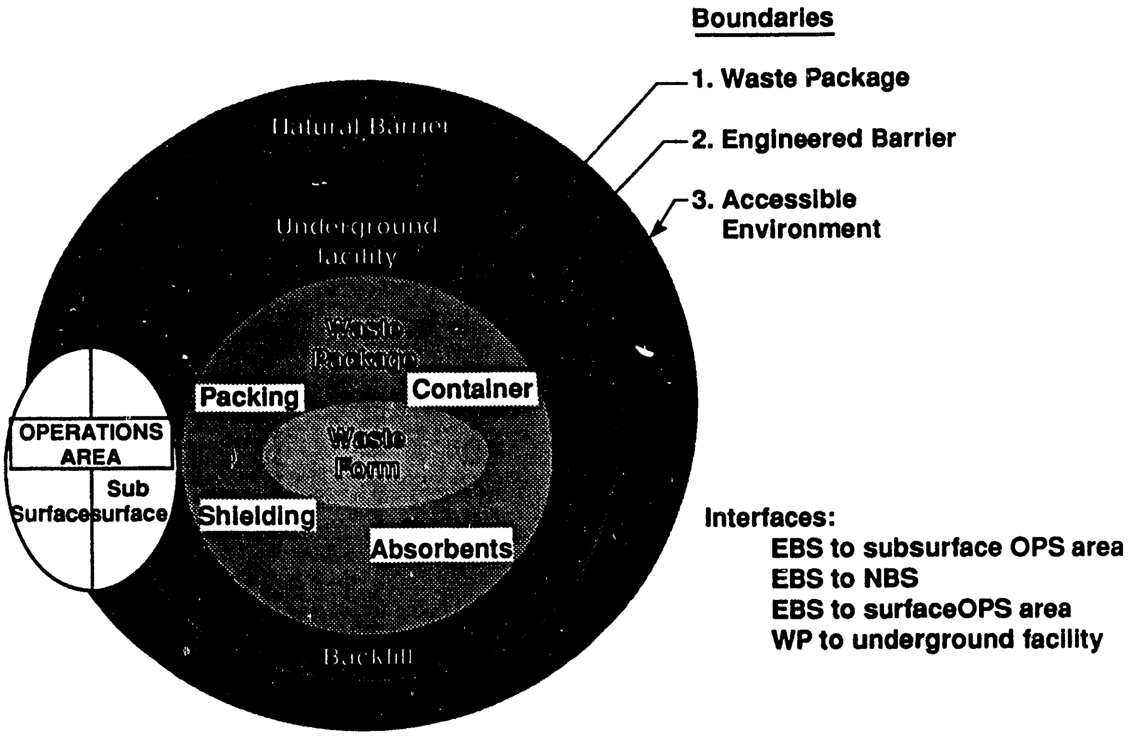


Figure 2. Geologic repository interfaces for EBS.

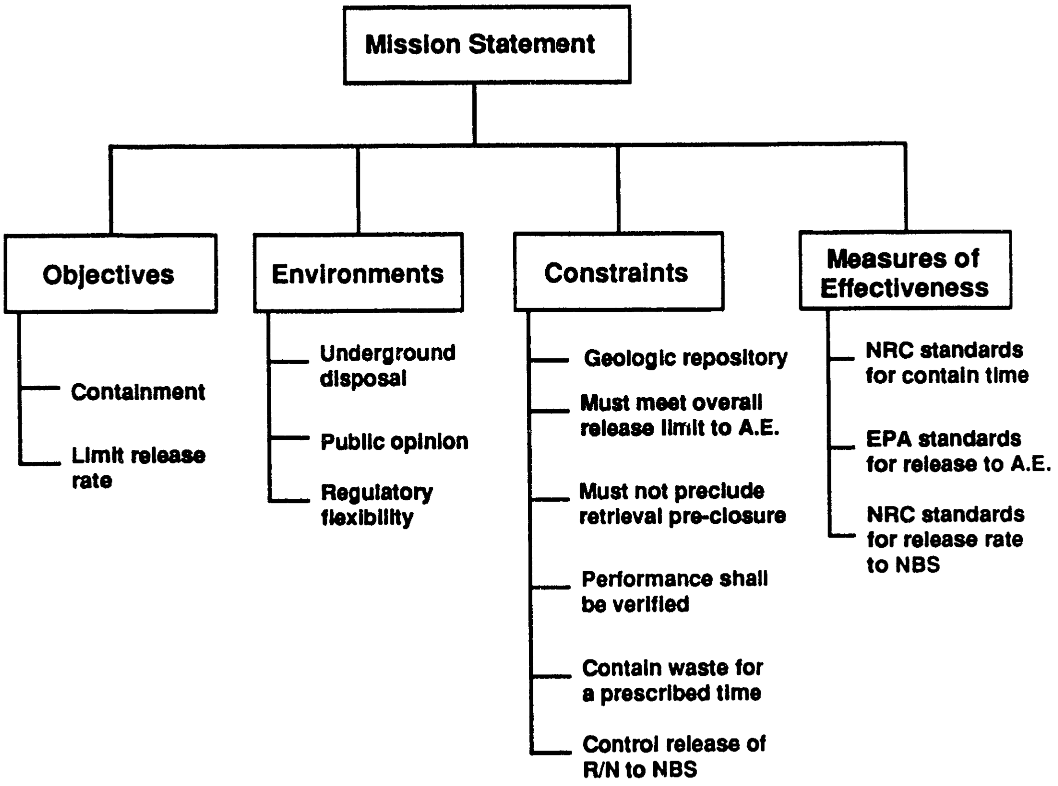


Figure 3. EBS mission is characterized by its objectives, environments, constraints, and measures of effectiveness.

approach, so that the total system will assure that any release of radionuclides to the accessible environment would conform to EPA standards.

In generating preliminary concept descriptions, we translated the mission requirement and known technological limitations into functions to be performed and requirements that define how well these functions are to be performed. In this beginning stage of development, we used general, nonquantitative objectives, environmental assumptions, constraints, and performance measures. Both the requirements and constraints evolved during the design development, starting with very broad needs, then becoming narrowed, and finishing with specific system needs, as shown in Fig. 4.

The constraints were driven by regulations, policies, and management guidance. The requirements and constraints have many sources, and all must be considered if the resulting design-concept description is to be acceptable. Figure 5 gives examples of regulatory and legal constraints; programmatic constraints; functional requirements; and limits of science, technology, and the environment.

In conducting the highly interactive and interdependent steps used to develop design-concept descriptions, we drew on the resources of knowledgeable technical specialists having expertise in engineering, metallic and nonmetallic materials, chemistry, geomechanics, hydrology, and geochemistry. To meet

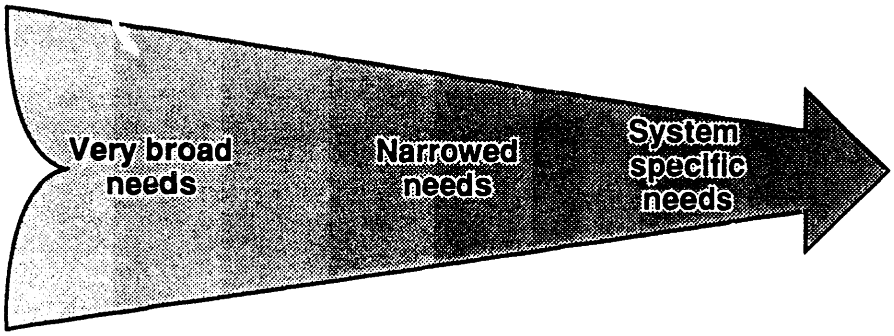


Figure 4. The requirements and constraints evolve during the design development.

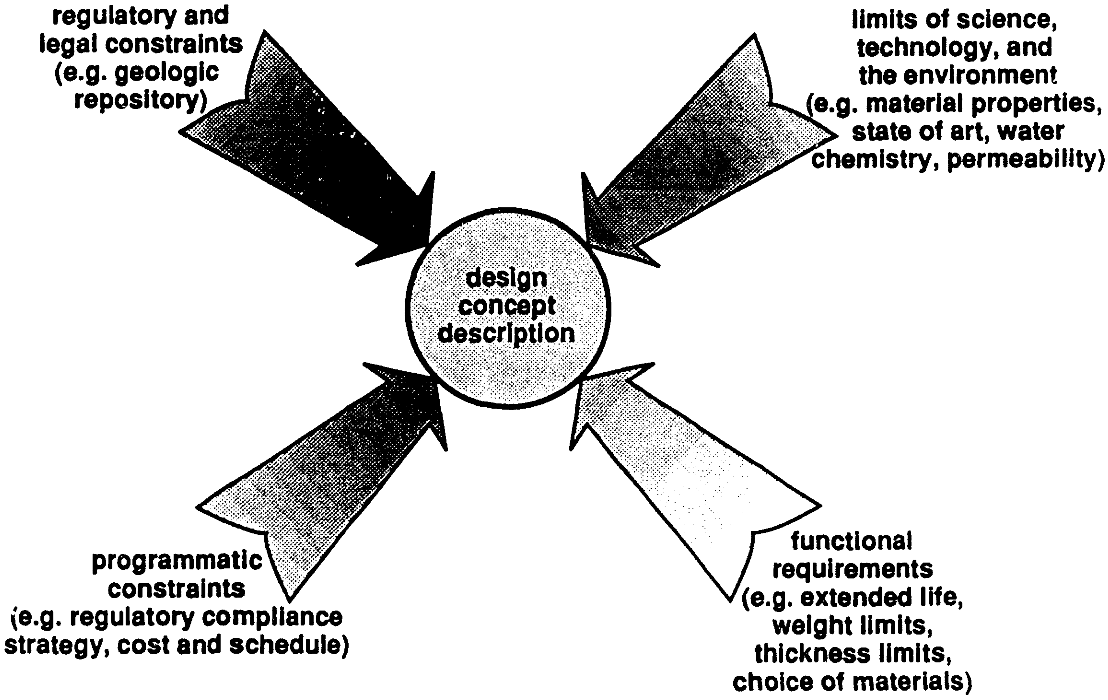


Figure 5. EBS concept descriptions must address all constraints and requirements and are limited by our understanding of the environment, scientific knowledge, and state of technology.

mission requirements for the EBS and its waste-package components, we used an iterative design concept. We started with broad interpretations of the constraints and requirements and with a general understanding of the scientific and technological limits that applied to the situation. We then developed concepts that allowed us to come to closure at each level of specificity, as shown in Fig. 6 by the arcs cutting each of the four major requirement spaces. After describing the system in general terms, we were able to be more specific (narrow our requirements) and come to closure again. Each source of requirements and constraints evolved from broad to specific, as represented by the examples in Fig. 7.

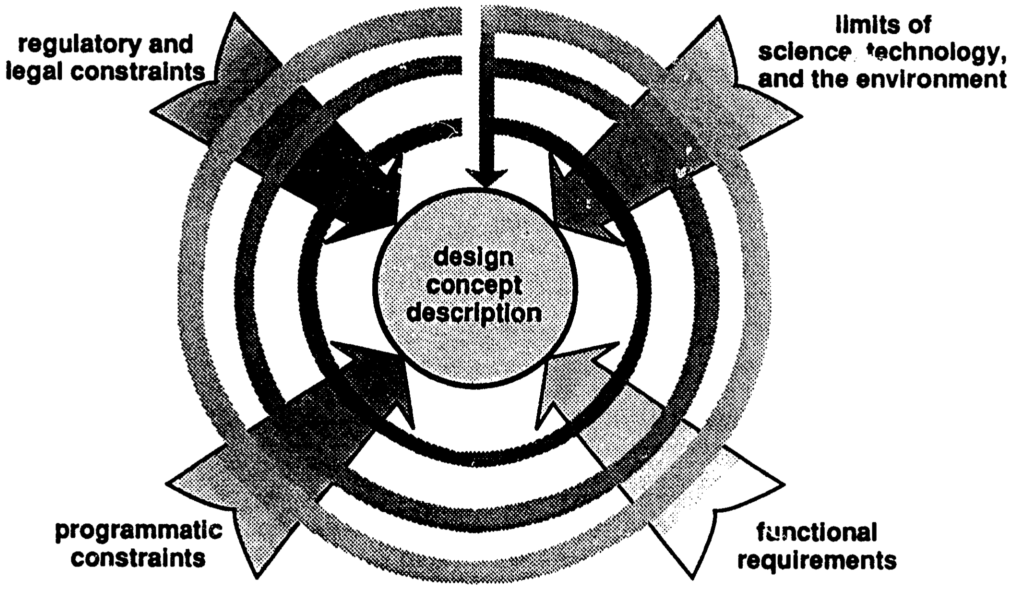


Figure 6. Concept development for the EBS and its waste package components is iterative to meet mission requirements.

Programmatic
- ☐ No limit on cost or schedule
  - ● Limit cost but not schedule
    - ▲ Limit cost and schedule

Regulatory and Legal
- ☐ Contain radionuclides (NWPA)
  - ● Contain radionuclides per EPA standards
    - ▲ Contain radionuclides per NRC & EPA standards

Functional
- ☐ Contain waste for a long time
  - ○ Contain waste for at least 1,000 years
    - △ Contain waste for greater than 10,000 years

Limitations of science and technology
- ☐ Use any material to contain waste
  - ● Use a specific material
    - ▲ Limit the material stress

Figure 7. Each source of requirements and constraints evolves from broad to specific.

Alternative concepts evolved from each design-development session. Minor variations, essentially designers' choices, were possible by choosing such things as alternative waste-package emplacement orientations (e.g., vertical or horizontal emplacement in an excavated cavity, or emplacement directly in the drift). Each particular choice created more specific requirements, which could be traded, so that additional design concepts evolved as a result of trade studies, optimizations, and hybrid concepts.

Concept Synthesis

The primary functions of the EBS are to contain waste and to limit release of radionuclides to the natural barrier system. These functions are accomplished by (1) preventing or delaying the transport of radionuclides through the surrounding materials; and (2) preventing or delaying movement of gases and liquids to and from the waste, or, if movement occurs, limiting the quantity of gases and liquids in contact with the waste.

To develop design features from the functions and requirements, we need to describe the operating environments, describe the system phenomena and processes, and incorporate processes and features that can enhance containment and hinder release. Table 1 provides a partial listing of some applicable phenomena and corresponding design features.

To generate preliminary concept descriptions, we use a tailored systems-engineering process that incorporates 10 iterative steps (Fig. 8):

(1) **Accommodating a key set of constraints and requirements into the concept generation.** All EBS concepts must be designed to address a key set of constraints and requirements, including containment of radionuclides for a prescribed period, limits on the release rate of any radionuclide, ability to retrieve the waste, ability to confirm performance, control of criticality, provision of unique identification, and materials properties and interaction.

Table 1. Environmental processes and some corresponding design features.

System Phenomenon/Process	Design Features to Enhance or Mitigate Process
Hydrology Fluid flow through fractures Fluid flow through matrix Imbibition	• Liners • Sealants • Vitrified rock adjacent to emplacement cavity • Packing materials • "Umbrellas" to divert water • Drainage schemes to channel water • Emplacement geometry • Containers
Radiation and heat Thermal radiation γ-rays, neutrons Convection Conduction Geochemical changes Phase transformations Water relocation Rock stress changes γ-radiation-induced changes	• Heat pipes and active cooling • Thermally activated barriers (e.g., asphalts, paraffins, chemically bonded ceramics) • Compatible materials high conductivity radiation tolerant temperature resistant • Heat tailoring fuel aging geometric distribution • Chemical stabilizers • Mechanical stabilizers • High-energy radiation (x-ray, γ-ray) barriers
Radionuclide release Gaseous release Ion exchange Dissolution of waste Colloid transport Diffusion Precipitation Advection	• Stabilizing buffers used as fillers or packing to control pH • Ion-exchange media • Flocculents • Stabilizing/encapsulating matrix • Precipitation agents • Low-permeability packing materials

Table 1 (cont'd)

System Phenomenon/Process	Design Features to Enhance or Mitigate Process
Container degradation General corrosion/oxidation Galvanic corrosion Crevice corrosion Stress-corrosion cracking Pitting Microbial attack Crack growth Dissolution Alteration	• Stabilizer (buffer) to control pH • Corrosion-resistant metals/alloys • Corrosion-allowance metals/alloys • Galvanic couples, sacrificial anodes • Crack resistant materials • Single-phase materials, nonmetallic materials (oxides, composites, graphites) • Joint-free construction, smooth surfaces, space-minimal reentrant geometries • Fuel aging to reduce temperatures • Lower density per unit area of waste packages to reduce temperatures • Compatible packing material
Radionuclide retardation Chemical bonding Mechanical filtering Sorption Matrix capture Ion exchange/isotope exchange	• Low-permeability materials • Absorbents/adsorbents • Emplacement geometry to maximize matrix capture • Ion-exchange media • Chemically reactive materials to bond nuclides at local sites

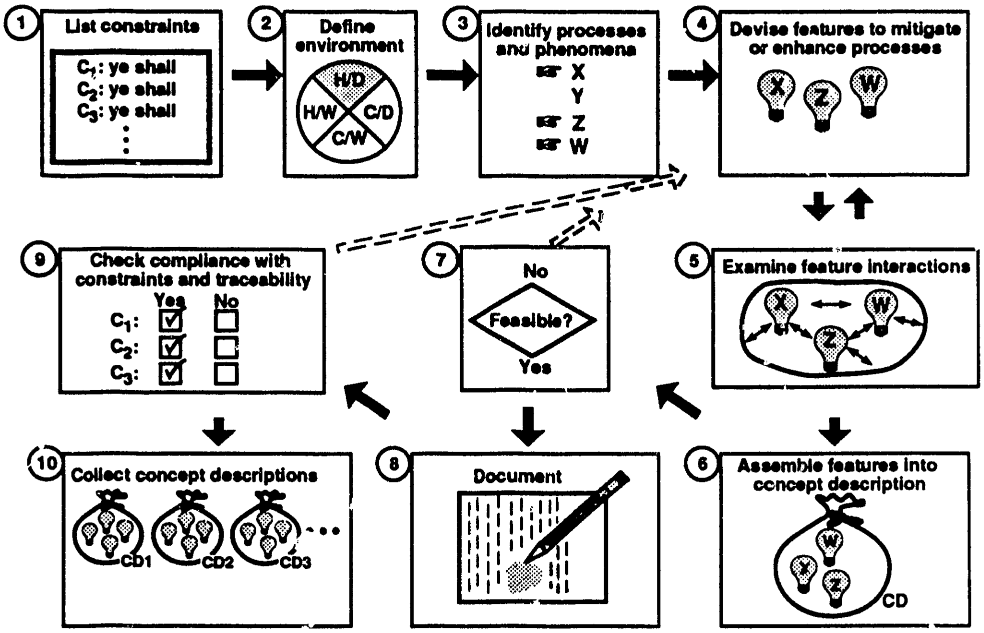


Figure 8. A tailored systems engineering process to generate preliminary concept descriptions.

(2) **Defining the operating environment in terms of the temperature and presence of water.** To focus our efforts and come to closure, we constrained the design environment to four fields representing conditions at the boundary between the EBS and the natural barrier system: hot and dry, cold and dry, cold and wet, and hot and wet. We defined hot as any temperature greater than or equal to the boiling point of water; cold as less than the boiling point of water; dry as the absence of liquid water; and wet as the presence of liquid water. We chose one of these four fields for each iteration. This approach permitted us to easily generate concepts that would be compatible with the varying conditions that the engineered barrier could see over its expected lifetime.

(3) **Identifying applicable processes for the given environment.** Examples of these processes include fluid flow through fractures and matrix; radionuclide retardation through sorption and ion exchange; materials degradation through corrosion and microbial attack; and radionuclide transport through diffusion and dissolution. Some of these processes may not be applicable for particular environmental fields chosen in the previous step.

(4) **Devising features to mitigate or enhance operable processes.** In this step, we accept or modify the near field and man-made environment, and we define information needs. For transport processes, we can prevent gas and liquid from reaching the waste; limit entry rate of the gas and liquid; limit egress rate of the gas and liquid; modify the near field and man-made environment to enhance positive effects and to mitigate negative effects; and choose barriers that limit entry and egress of radionuclides. For extended life, we can choose materials most resistant to degradation; choose materials most compatible with the environment; add stabilizers to mitigate effects of the environment; and modify the environment for compatibility with the materials.

(5) **Examining the design features interactions.** We examine the interactions of design feature with each other and with the environment. The features must interact positively, and the in situ properties must not compromise their functions. Any compromise indicates a return to the previous step. We then refine information needs.

(6) **Assembling the features into an integrated concept description.** We assemble (synthesize) the features and document the ideas by sketching the assembly and annotating the sketch with descriptions and dimensions.

(7) **Determining feasibility.** We check the feasibility, estimate performance, and perform calculations with simple models. We again refine information needs.

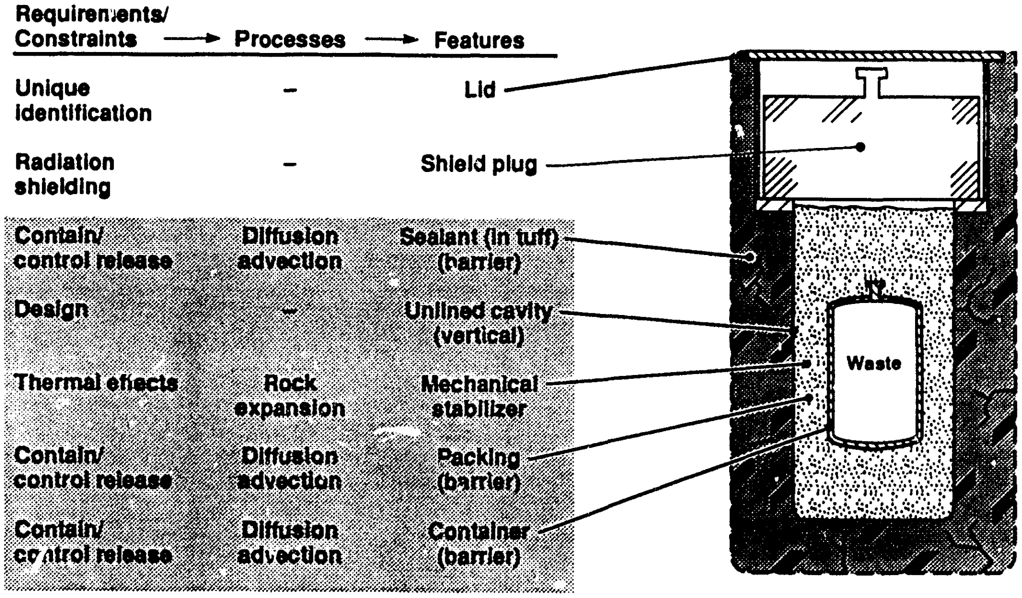
(8) **Generating a records package.** For each concept description, we generate a records package that includes an integrated drawing with annotations—e.g., descriptions of interactions, estimates of performance, preliminary calculations, and judgment calls—and a list of associated requirements, assumptions, and constraints. We use this records package to trace design features to higher levels of functions, requirements, and system descriptions.

(9) **Checking for compliance with all constraints and requirements.** We verify that functions, constraints, requirements, and features can be traced through their predecessors and parent/child relationships and that none of the higher-level constraints and requirements have been overlooked.

(10) **Collecting the preliminary concept descriptions for subsequent processing, modification, ranking, and selection.** Each concept description is reiterated through the process with modified or new constraints. Each concept description is modified for other environmental fields that were not addressed during the previous iterations. Initial screening may be done in this step to group concept descriptions with similar attributes. This grouping may be helpful in reducing the number of concepts to an acceptable number. The level of detail and the duration of the iteration cycles were generally limited by available time, cost, and management decisions.

Preliminary Concepts

In Figs. 9 through 12, we show four preliminary concepts that represent diverse ideas, emplacement



Requirements/ Constraints	→ Processes	→ Features
Unique identification	-	Lid
Radiation shielding	-	Shield plug
Contain/ control release	Diffusion advection	Sealant (in tuff) (barrier)
Design	-	Unlined cavity (vertical)
Thermal effects	Rock expansion	Mechanical stabilizer
Contain/ control release	Diffusion advection	Packing (barrier)
Contain/ control release	Diffusion advection	Container (barrier)

Figure 9. Sealed borehole container concept.

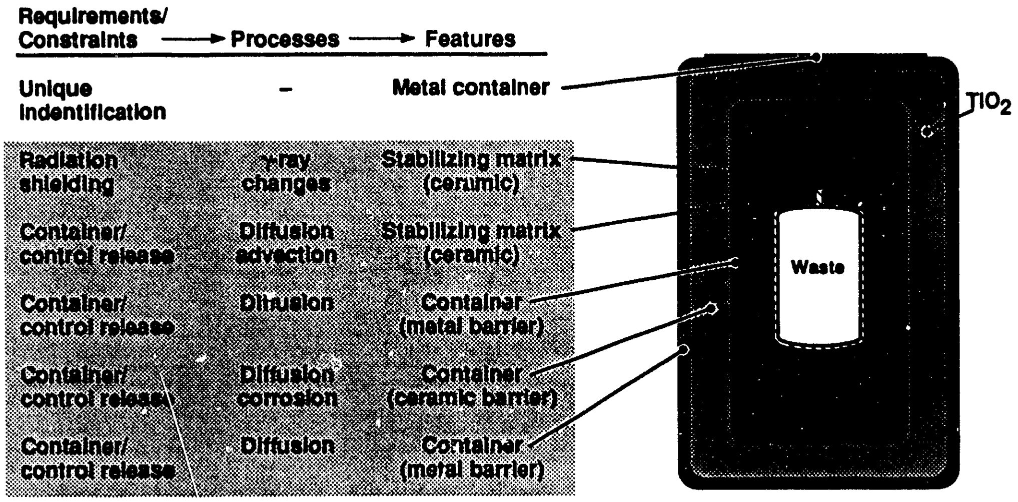


Figure 10. Ceramic container concept.

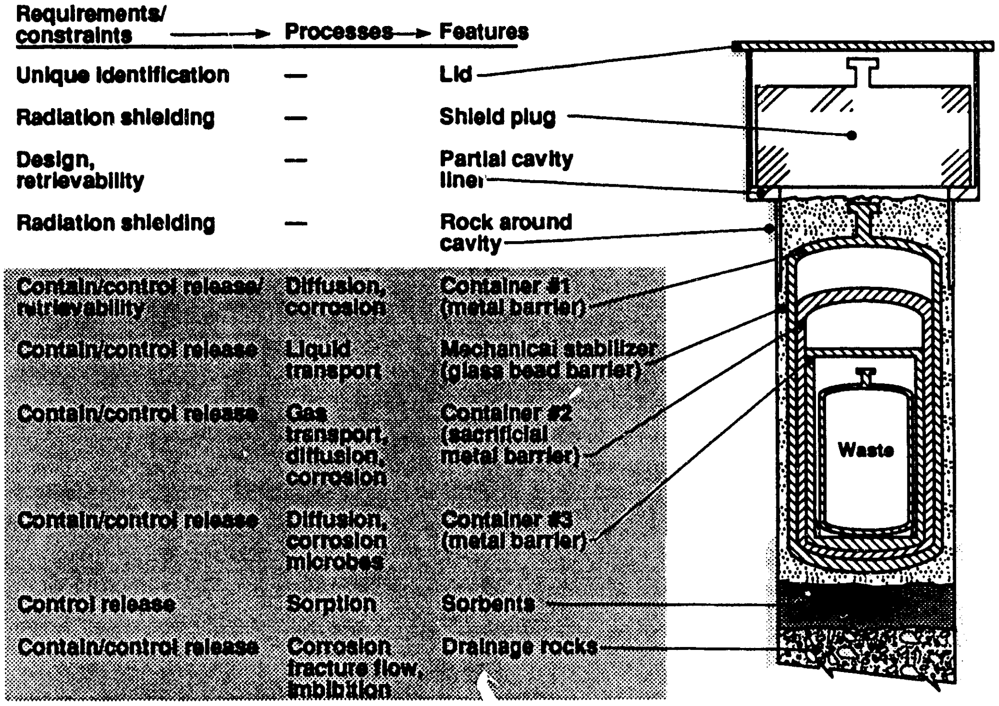


Figure 11. Metal multiwalled container concept.

geometries, and materials. Figure 9 shows a concept that incorporates a sealant pumped into the near field to fill fissures. The waste is surrounded by a granulated mechanical stabilizing material that is filled with a liquid packing material (cementitious, asphaltic, or other). This design is applicable only for vertical emplacements.

Figure 10 shows a concept that is independent of emplacement geometry. The waste is placed in a sealed thin-walled metal container, surrounded by a ceramic stabilizing matrix (probably Al_2O_3), and then cold isostatically pressed at 20,000 psi. The cold-pressed container is then placed in another container made of thin stainless steel, surrounded by granular TiO_2, and hot isostatically pressed at 30,000 psi and 900°C until the TiO_2 is compressed to 99% theoretical density. TiO_2 is very stable in natural groundwater media and is thermodynamically stable.

Figure 11 shows a multiwalled metal container utilizing galvanic couples for extended life. The waste form is contained in a copper container placed inside a

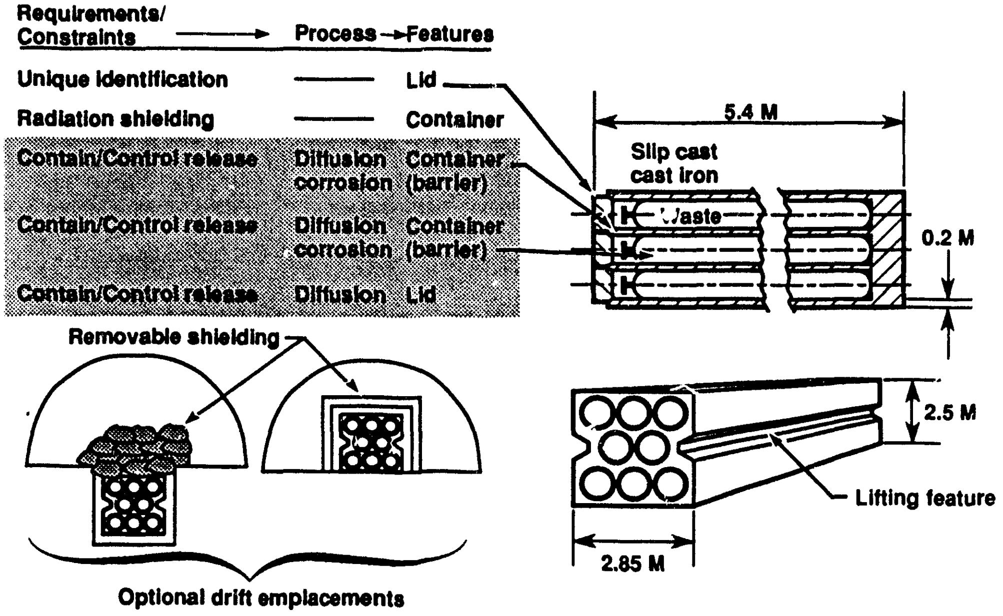


Figure 12. Drift emplaced cast iron concept.

high-nickel-alloy container that, in turn, is placed inside a wrought-iron outer container. Each container has walls about 3 cm thick.

Figure 12 shows a drift-emplaced cast-iron cask into which individual sealed stainless-steel waste containers are placed. The iron cask becomes a corrosion-allowance barrier between the waste and the environment.

Requirements Documents

A design-requirements document for each of two or more selected concepts will be developed, reviewed, and approved prior to beginning the Advanced Conceptual Design phase. Interfaces with other parts of the system will be identified. All design assumptions will be clearly stated for subsequent validation.

Ranking and Selection

Once the final set of concept descriptions has been developed, we plan to use a structured, analytical framework to evaluate the alternative concepts. To be objective, the selection factors must be relevant to requirements; must be broad, independent, measurable, and understood; and must be differentiated without bias.

We have chosen to use Decision Analysis[5] as our analytical framework. This method, which uses the logic flow shown in Fig. 13, will help us determine how well the relative performances of the alternative concepts can be predicted over time and will give us a systematic and documented decision about the concepts to be carried into the next design phase of the waste-management program. Decision Analysis methodology has been used extensively in the nuclear industry for evaluating the safety of

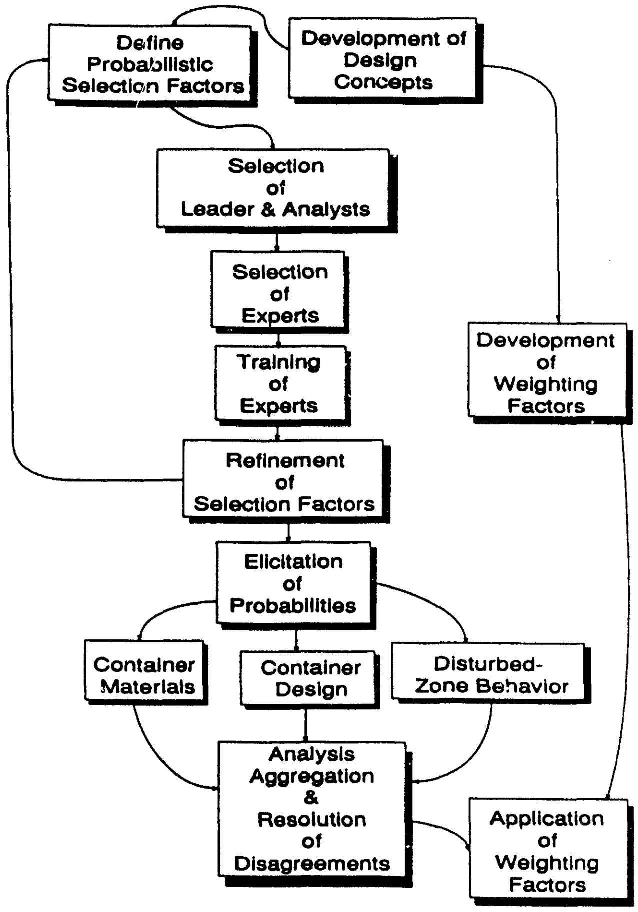


Figure 13. Logic flow for decision analysis method.

reactors,[6,7] and has been advocated for applications in mined geologic disposal of radioactive waste.[8,9] Similar methods have been proposed for the evaluation of waste-package performance.[10] The method is slightly different than most other evaluation methods in that the experts who influence and refine the selection factors are trained in probability estimation. We will conduct a preliminary screening to reduce the number of alternatives to a manageable set for detailed evaluation, and the experts will then evaluate that set of alternatives.

Table 2 lists possible factors that may be used in the evaluation of alternative concepts. After probabilities have been elicited, weighting may be applied to each factor, and totals obtained to tentatively rank alternative concepts. However, to reduce the effects of evaluator bias, the weighting values may be withheld until after the factors have been scored.

If any sensitivities are discovered for the probability estimates, the factors and weights will be reviewed for possible modification, and the impact of relaxing the requirements that cause the sensitivities will be evaluated. If any sensitivities must be removed, appropriate, recommendations will be made for changing the requirements that create the sensitivities.

Summary

We have developed several preliminary design concepts for an Engineered Barrier System and waste packages to be used at the proposed Yucca Mountain repository, and we have described a candidate set of factors for selecting among alternative design concepts. However, we cannot complete the design process until we gain access to the underground horizon at Yucca Mountain.

We have much work remaining in the Conceptual Design phase. We must iterate present and future design concepts to sufficient detail to allow reasonable assessment of their performance characteristics. Only then can we begin the ranking and selection processes to narrow the number of concepts to be carried into the Advanced Conceptual Design phase of the Waste Package Plan.

Table 2. Examples of selection factors.

Major Area	Description	Selection Factor
Container Design	Provide evaluation that the proposed design will meet the "Substantially Complete Containment" requirement of 10 CFR 60.113A.[11]	Probability that containment can be predicted for 1000 years.
	Evaluation of ability of the design to meet requirements for limited release for 1,000 to 10,000 years per 10 CFR 60.113B.	Probability that release rates can be predicted from 1,000 to 10,000 years.
	Assurance retrievability requirements can be met.	Probability the container can be retrieved up to 50 years.
	Assess the inspectability and assurance that the design meets engineering requirement after construction.	Probability the design can be inspected and monitored.
	Assess compliance with health and safety regulations.	Probability the design will meet radiological and safety requirements.
	Schedule.	Probability that the schedule can be met.
	Cost.	Probability the design can be constructed within cost.
Container Materials	Assures the materials corrosion behavior can be predicted.	Probability the materials corrosion properties can be predicted over 10,000 years.

Table 2 (cont'd)

Major Area	Description	Selection Factor
	Stability of basic material properties for 10,000 years.	Probability the material will remain stable during the emplacement period.
	Assess potential for microbial corrosion of the container.	Probability of microbial corrosion not occurring.
	Assess the potential mechanical degradation mechanisms.	Probability of creep and/or fatigue and/or environmental assisted cracking and/or hydrogen embrittlement or other pertinent degradation mechanisms will not occur.
	Assure adequate strength and toughness to bear emplacement and retrieval loads.	Probability that selected material will remain strong and tough enough during retrieval period.
	Assess potential fabrication problems and their impact on the performance of the container.	Probability the Material can be fabricated to the design requirements.
Disturbed Zone	Prediction of near-field behavior over 10,000 years.	Probability the thermal hydraulic behavior of the near-field can be accurately predicted.
	Assess influence of design (thermal load, SF age, etc.) on the other selection factors, i.e., allow a geochemically predictable environment.	Probability that the near-field will remain geochemically predictable for 10,000 years.
	Assess the potential for container-geochemical interaction.	Probability the container or corrosion products will not interact with surrounding materials.

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