WBS: 1.2.1

QA: QA |

**Civilian Radioactive Waste Management System
Management & Operating Contractor**

License Application Design Selection Report

B00000000-01717-4600-00123 REV 01 ICN 01

August 1999

Prepared for:

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Under Contract Number
DE-AC08-91RW00134

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CHANGE HISTORY

<u>Revision Number</u>	<u>Interim Change No.</u>	<u>Effective Date</u>	<u>Description of Change</u>
0	0	04/15/99	Initial issue.
1	0	05/28/99	As part of the U.S. Department of Energy acceptance review of REV 00 conducted in accordance with QAP 6.2, <i>Document Review</i> , significant changes were made throughout the document. The results, conclusions, and recommendations did not change; however, the contents were changed and supplemented to clarify and expand on the discussions provided in REV 00.
1	1	08/30/99	Replaced Phase II evaluation criterion "Licensing Probability/Safety" with "Performance Demonstrability." Added summary of policy guidance and direction from the License Application Design Integration Group as Appendix B. Updated reference section to replace QAP-3-12, <i>Transmittal of Design Input</i> , data transmittals with their completed QAP-3-5, <i>Development of Technical Documents</i> , technical reports and to correct the reference tracking number for Stinebaugh et al. (1989). Revised text with minor editorial corrections. Pages affected are: i, iii, v, vii, xiv, xv, xxi, O-7, O-13, O-16, O-20, O-22, O-24, 1-1, 1-2, 1-4, 1-5, 2-2, 3-2, 3-6, 3-10, 4-1, 4-6, 5-2, 5-4, 5-6, 5-17, 5-32, 5-33, 5-34, 5-36, 5-39, 5-41, 5-45, 5-48, 5-49, 5-51, 5-54, 5-58, 5-59, 6-3, 6-4, 6-5, 6-6, 6-7, 6-9, 6-10, 6-11, 6-13, 6-15, 7-2, 7-3, 7-7, 8-1, 8-3, 8-4, 8-5, 8-6, 8-11, 8-13, Appendix B (all pages), Appendix C (all pages), and Appendix D (all pages). Pages added are: 8-1a and 8-1b.

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EXECUTIVE SUMMARY

Background

In December 1998, the U.S. Department of Energy (DOE) published the *Viability Assessment of a Repository at Yucca Mountain* (DOE 1998b). The Viability Assessment described a preliminary design of a potential repository at Yucca Mountain, Nevada, for disposal of spent nuclear fuel and high-level radioactive waste, and assessed the probable behavior of that repository design in the Yucca Mountain geologic setting. The report concluded that “Yucca Mountain remains a promising site for a geologic repository and that work should proceed to support a decision in 2001 on whether to recommend the site to the President for development as a repository” (DOE 1998b, Overview, p. 2). It also concluded that “uncertainties remain about key natural processes, the preliminary design, and how the site and design would interact” (DOE 1998b, Overview, p. 2). Recognizing that the design that was evaluated will be refined before a license application could be submitted, the Viability Assessment notes that “DOE is evaluating several design options and alternatives that could reduce existing uncertainty and improve the performance of the repository system” (DOE 1998b, Overview, p. 30).

During the preparation of the Viability Assessment, the DOE asked the Management and Operating Contractor (M&O) for the Civilian Radioactive Waste Management Program to study alternative design concepts for a potential geologic repository for high-level radioactive waste at Yucca Mountain. The License Application Design Selection (LADS) project was initiated to conduct that study. The goal of the project was to develop and evaluate a diverse range of conceptual repository designs that work well in concert with the Yucca Mountain site and to recommend an initial design concept for the possible Site Recommendation and License Application. This report presents the results of the LADS project.

Design Process

The LADS project was conducted by a core team of senior technical staff supported by the entire M&O organization, decision analysis consultants, an external review group established for this study, and both DOE and M&O senior management. Representatives of the DOE and of internal and external oversight organizations observed key steps in the process and provided valuable comments and suggestions as the study progressed.

The design process consisted of two phases. In Phase I, a series of basic design concepts (design alternatives) and components (design features) were analyzed for their potential value as elements of a repository design. Using this information, a diverse set of enhanced design alternatives was created. In Phase II, these enhanced design alternatives were refined, screened for acceptable postclosure performance, and evaluated against a set of criteria addressing four broad aspects of the repository: performance demonstrability; flexibility; construction, operations, and maintenance; and cost. Based on this evaluation, the combined LADS core team and M&O management group recommended a conceptual design to the DOE.

While the design effort was conceptual in nature, sufficient design detail was provided to allow the differences in design concepts to be clearly understood. However, the details specified for

purposes of analysis are not firmly fixed, and further refinement is required to bring the recommended conceptual design to the level of detail needed for a possible Site Recommendation and License Application. The development of a License Application design will necessarily be an iterative process, involving newly acquired scientific information, evolution of performance assessment models, and design evolution starting from the recommended design described in the following section.

Recommended Design

The recommended repository concept can be characterized as a low thermal impact design. This design uses more extensive thermal management techniques than the Viability Assessment design to limit the impacts of the heat released by the waste. These thermal management techniques include thermal blending of spent nuclear fuel assemblies, closer spacing of the waste packages, wider spacing of the waste emplacement tunnels (drifts), and preclosure ventilation. Thermal blending of spent nuclear fuel assemblies reduces the peak heat output of the waste packages, making it easier to limit temperatures in the rock around the waste packages. Close spacing of the waste packages in the emplacement drifts reduces temperature variations in the drifts, simplifies the analysis of the effects of heat, and reduces the total length of drifts excavated. Spacing the drifts further apart reduces the effects of the heat from each drift on its neighbors, leaves a wide region of rock between drifts that stays below the boiling point of water so that water can move around the hot drifts and flow down through the cooler areas, and limits the long-term alterations to the repository rock caused by the heat from the waste. Preclosure ventilation makes it possible to stay within temperature limits in the rock and around the waste packages during operation despite the much closer waste package spacing, and reduces maximum temperatures after closure by removing energy before closure that would otherwise heat the repository rock.

The recommended design differs from the Viability Assessment design in a number of other important aspects. While both use a two-layer waste package, the recommended design places the corrosion-resistant material on the outside rather than the inside to provide long-term protection to the more corrosion-susceptible structural material. The recommended design also adds defense in depth with a drip shield covered by backfill to protect the waste packages from dripping water while they are hot enough to be susceptible to localized corrosion. Finally, the recommended design uses steel structural materials in the drifts instead of the concrete evaluated in the Viability Assessment design in order to avoid the possible impacts of the chemicals in the concrete on mobilization and movement of radionuclides. A comparison of some of the differences is shown in Figure ES-1.

Basis for Recommendation

The recommended design provides a good balance of the ability of lower temperature designs to reduce uncertainties about postclosure performance and the preclosure advantages that designs with greater thermal effects can offer in the areas of construction and operations, flexibility, and cost.

Performance—Projections of performance using central estimates and total system performance assessment-Viability Assessment models indicate that the recommended design, if implemented at Yucca Mountain, would perform extremely well with respect to a screening criterion of 25 millirem/year to an average member of a critical group living 20 kilometers from the potential repository during the first 10,000 years. A calculated dose rate of 25 millirem/year would not be reached for more than 300,000 years, and the dose rate at any time would be less than 100 millirem/year. The calculated time of the first corrosion failure of a waste package is about 100,000 years.

Reduced Uncertainty—The recommended design offers a number of advantages for the licensing safety case compared with designs with greater thermal effects (including the Viability Assessment design). First, it reduces or avoids uncertainties associated with the thermal pulse when large quantities of water could possibly pool above the repository and then subsequently flow into the drifts where the water could corrode the hot drip shields or waste packages. It does this by keeping larger areas of very wide pillars cool enough to allow water to move around the drifts and drain through the pillars. Second, by allowing only a small amount of the rock mass several meters around the drifts to exceed the boiling point of water for several hundred years, the design reduces the potential for long-term hydrological and geochemical alteration of the host rock. This is expected to reduce the uncertainties associated with modeling the performance of the host rock. Third, the wide drift spacing reduces the analytical complexities resulting from temperature interactions among closely spaced drifts, simplifying the analysis of repository performance. Fourth, the design does not subject the Alloy-22 waste package material to temperature/humidity conditions conducive to aggressive crevice corrosion. As a result of both thermal conditions and the diversion of water by the drip shield, the Alloy-22 waste package material is subject only to very slow general corrosion.

Construction/Operations—The recommended design achieves many of the operational benefits of designs having more extensive thermal effects in terms of the ability to use larger waste packages and reduce the length of emplacement drifts that must be excavated. In contrast, the lowest temperature design that was considered required 60 percent more waste packages, and more than twice the length of emplacement drifts, with a proportionate increase in the probability of industrial accidents during construction and operation. The recommended design also provides operational flexibility by allowing cooler spent nuclear fuel and DOE high-level radioactive waste to be placed into drifts separate from the hotter spent nuclear fuel if appropriate. This avoids the need for careful staging and sequencing of the emplacement of DOE and commercial waste packages assumed in both the Viability Assessment design and the enhanced design alternatives with more extensive thermal effects.

Technical and Programmatic Flexibility—The recommended design allows focused progress toward a final design for a possible Site Recommendation and License Application, without precluding future revision of major program goals or repository design attributes. For example, transition to either higher or lower temperature goals is possible should these be deemed appropriate later. Specifically, no additional technology development or site characterization would be needed to allow transition to lower temperature goals by extending the preclosure ventilation period. In addition, although the design requires 40 percent more area than the Viability Assessment design, it still leaves room to accommodate 105,000 metric tons of waste

(if such an increase in capacity were authorized) within an area that has already been characterized.

Cost—The estimated cost of the recommended design is similar to the cost of the designs with greater thermal effects and is 25 percent lower than the lowest-temperature design considered. Although the estimated cost is about 20 percent higher than the Viability Assessment design, most of these costs are associated with fabrication and emplacement of the drip shield and backfill and would not be incurred until closure of the repository. The net present value cost of the recommended design, which takes into account the long delay in the expenditures for the drip shields and backfill, is only about 8 percent higher than the net present value of the Viability Assessment design.

Figure ES-1. Comparison of Key Design Attributes Between Enhanced Design Alternative II and the Viability Assessment Design (in-drift barriers, waste package materials, waste package and drift spacing, and subsurface ventilation)

CONTENTS

	Page
EXECUTIVE SUMMARY.....	vii
O. OVERVIEW.....	O-1
O.1 BACKGROUND AND GOALS OF THE STUDY	O-1
O.2 DESIGN PROCESS.....	O-2
O.2.1 Phase I–Evaluation of Independent Design Alternatives and Design Features.....	O-2
O.2.1.1 Phase I Evaluation Criteria	O-3
O.2.1.2 Identification and Evaluation of Candidate Design Elements	O-3
O.2.1.3 Development of Enhanced Design Alternatives	O-5
O.2.1.4 Criteria for Evaluating Enhanced Design Alternatives in Phase II	O-6
O.2.1.5 Enhanced Design Alternative Development Workshop	O-7
O.2.2 Phase II–Refinement and Evaluation of Enhanced Design Alternatives	O-9
O.2.2.1 Selection of Final Set of Enhanced Design Alternatives for Phase II	O-9
O.2.2.2 Evaluation Using the Phase II Criteria	O-12
O.2.2.3 Comparative Evaluation of the Enhanced Design Alternatives.....	O-20
O.3 DESIGN RECOMMENDATION.....	O-21
O.3.1 Key Elements of the Recommended Design.....	O-24
O.3.2 Major Characteristics of the Recommended Design.....	O-25
1. INTRODUCTION.....	1-1
1.1 OBJECTIVE.....	1-2
1.2 SCOPE	1-3
1.3 BACKGROUND.....	1-4
1.3.1 U.S. Nuclear Regulatory Commission Regulations.....	1-4
1.3.2 U.S. Department of Energy Level 2 Milestone.....	1-4
1.3.3 Management and Operating Contractor Level 3 Milestone.....	1-4
1.3.4 License Application Design Selection Team	1-4
1.3.5 Environmental Considerations.....	1-5
1.4 QUALITY ASSURANCE	1-6
2. REQUIREMENTS AND ASSUMPTIONS.....	2-1
3. PROCESS	3-1
3.1 ATTRIBUTES OF OVERALL DECISION PROCESS.....	3-1
3.2 PRINCIPAL TASKS IN THE PROCESS	3-4

CONTENTS (Continued)

	Page
4. DESIGN ALTERNATIVES AND DESIGN FEATURES.....	4-1
4.1 SELECTION OF DESIGN FEATURES AND DESIGN ALTERNATIVES FOR PHASE I.....	4-1
4.2 DESIGN FEATURE/DESIGN ALTERNATIVE EVALUATION CRITERIA	4-7
4.2.1 Introduction	4-7
4.2.2 Design Feature/Design Alternative Evaluation Criteria.....	4-8
4.2.3 Phase I Evaluation Criteria Expressed as Questions	4-8
4.2.4 Confidence Assessment.....	4-12
4.3 DESIGN ALTERNATIVE DESCRIPTIONS	4-12
4.3.1 Design Alternative 1–Tailored Waste Package Spatial Distribution	4-12
4.3.2 Design Alternative 2–Low Thermal Load	4-13
4.3.3 Design Alternative 3–Postclosure Ventilation	4-13
4.3.4 Design Alternative 4–Enhanced Access Design	4-13
4.3.5 Design Alternative 5–Modified Waste Emplacement Mode Design	4-13
4.3.6 Design Alternative 6–Viability Assessment Design	4-14
4.3.6.1 Evaluation Summary.....	4-15
4.3.6.2 Confidence Assessment Summary.....	4-15
4.3.7 Design Alternative 7–Viability Assessment Design with Options	4-16
4.3.8 Design Alternative 8–Modular Design/Phased Construction	4-16
4.4 DESIGN FEATURES DESCRIPTIONS.....	4-16
4.4.1 Ceramic Coatings	4-16
4.4.2 Backfill	4-17
4.4.3 Drip Shield	4-17
4.4.4 Preemplacement Aging and Blending of Waste	4-17
4.4.5 Continuous Preclosure Ventilation.....	4-17
4.4.6 Rod Consolidation.....	4-18
4.4.7 Timing of Repository Closure and Maintenance of Underground Facilities and Ground Support	4-18
4.4.8 Drift Diameter	4-18
4.4.9 Waste Package Spacing and Drift Spacing	4-19
4.4.10 Waste Package Self-Shielding	4-19
4.4.11 Waste Package Corrosion-Resistant Materials (Metal and Ceramic)	4-19
4.4.12 Richards Barrier	4-19
4.4.13 Diffusive Barrier Under the Waste Package/Getter Under the Waste Package	4-20
4.4.14 Canistered Assemblies	4-20
4.4.15 Additives and Fillers	4-20
4.4.16 Ground Support Options	4-20
4.4.17 Near-Field Rock Treatment During Construction.....	4-21
4.4.18 Surface Modifications	4-21
4.4.19 Repository Horizon Elevation.....	4-21
4.4.20 Higher Thermal Loading.....	4-21

CONTENTS (Continued)

	Page
5. ENHANCED DESIGN ALTERNATIVES	5-1
5.1 ENHANCED DESIGN ALTERNATIVE DEVELOPMENT	5-2
5.1.1 Information Available Prior to the Workshop	5-2
5.1.2 Enhanced Design Alternative Workshop Process	5-3
5.1.2.1 Review of Individual Design Alternative and Design Feature Evaluations (General Session on Days 1, 2, and 3)	5-3
5.1.2.2 Division into Working Breakout Teams	5-7
5.1.2.3 First Pass by Enhanced Design Alternative Teams (Breakout Session on Day 4)	5-8
5.1.2.4 Second Pass by Enhanced Design Alternative Teams: Refinement and Reduction of Candidate Enhanced Design Alternatives (Breakout Session on Day 6, Morning)	5-11
5.1.2.5 Consideration of Performance Assessment, Defense in Depth, and Cost, and Refinement of Candidate Enhanced Design Alternatives (Breakout Sessions on Days 7 and 8)	5-12
5.1.2.6 Selection of Enhanced Design Alternatives (General Session on Days 9 and 10)	5-12
5.1.3 Enhanced Design Alternatives Developed in Workshop	5-13
5.1.3.1 Low-Temperature Designs	5-13
5.1.3.2 High-Temperature Designs	5-15
5.1.3.3 Enhanced Access Designs	5-16
5.1.4 Selection of Enhanced Design Alternatives for Phase II	5-17
5.1.4.1 Criteria and Guidance for Repository Enhanced Access Design	5-18
5.1.4.2 Final Enhanced Design Alternative Definition	5-18
5.1.5 Standard Features and Design Rationale for Enhanced Design Alternatives	5-19
5.1.5.1 Defense in Depth	5-19
5.1.5.2 Waste Package Design	5-21
5.1.5.3 Ground Support and Invert Materials	5-21
5.1.5.4 Standardization of Drift Diameter for all Enhanced Design Alternatives	5-21
5.1.5.5 Thermal Management	5-22
5.1.6 Use of Design Alternatives in Enhanced Design Alternatives	5-24
5.1.6.1 Design Alternative 1–Tailored Waste Package Spatial Distribution	5-25
5.1.6.2 Design Alternative 2–Low Thermal Load	5-26
5.1.6.3 Design Alternative 3–Postclosure Ventilation	5-26
5.1.6.4 Design Alternative 4–Enhanced Access	5-27
5.1.6.5 Design Alternative 5–Modified Waste Emplacement Modes	5-28

CONTENTS (Continued)

	Page
5.1.6.6 Design Alternative 6 and Design Alternative 7–The Viability Assessment Design and the Viability Assessment Design with Options.....	5-28
5.1.6.7 Design Alternative 8–Modular Design/Phased Construction.....	5-29
5.1.7 Design Features Not Selected for Enhanced Design Alternatives.....	5-29
5.1.7.1 Getter Under the Waste Package	5-30
5.1.7.2 Near-Field Rock Treatment During Construction	5-30
5.1.7.3 Surface Modifications.....	5-31
5.1.7.4 Repository Horizon Elevation	5-31
5.2 ENHANCED DESIGN ALTERNATIVE EVALUATION CRITERIA	5-32
5.2.1 Introduction	5-32
5.2.2 Enhanced Design Alternative Evaluation Criteria	5-33
5.2.2.1 Performance Demonstrability	5-33
5.2.2.2 Construction, Operations, and Maintenance.....	5-35
5.2.2.3 Flexibility.....	5-36
5.2.2.4 Cost/Schedule	5-36
5.3 ENHANCED DESIGN ALTERNATIVES EVALUATION SUMMARY.....	5-37
5.3.1 Description of Enhanced Design Alternative I	5-40
5.3.1.1 Enhanced Design Alternative I Evaluation Summary	5-41
5.3.1.2 Cost/Schedule	5-43
5.3.2 Description of Enhanced Design Alternative II.....	5-44
5.3.2.1 Enhanced Design Alternative II Evaluation Summary.....	5-45
5.3.2.2 Cost/Schedule	5-47
5.3.3 Description of Enhanced Design Alternative III.....	5-47
5.3.3.1 Enhanced Design Alternative III Evaluation Summary.....	5-48
5.3.3.2 Cost/Schedule	5-53
5.3.4 Description of Enhanced Design Alternative IV.....	5-53
5.3.4.1 Enhanced Design Alternative IV Evaluation Summary	5-54
5.3.4.2 Cost/Schedule	5-56
5.3.5 Description of Enhanced Design Alternative V.....	5-57
5.3.5.1 Enhanced Design Alternative V Evaluation Summary.....	5-58
5.3.5.2 Cost/Schedule	5-61
5.3.6 General Observations From the Evaluation of Enhanced Design Alternatives.....	5-61
5.3.7 Viability Assessment Design Cost Comparison.....	5-62
6. COMPARATIVE EVALUATION OF ENHANCED DESIGN ALTERNATIVES	6-1
6.1 ENHANCED DESIGN ALTERNATIVE COMPARATIVE EVALUATION METHODS	6-1
6.2 ENHANCED DESIGN ALTERNATIVE RANKING.....	6-3
6.2.1 Enhanced Design Alternative Ranking for Performance Demonstrability Criterion	6-3
6.2.2 Enhanced Design Alternative Ranking for the Flexibility Criterion	6-6

CONTENTS (Continued)

	Page
6.2.3 Enhanced Design Alternative Ranking for the Construction, Operations, and Maintenance Criterion	6-7
6.2.4 Enhanced Design Alternative Ranking for Cost Criterion.....	6-9
6.3 RESULTS OF RANKING THE ENHANCED DESIGN ALTERNATIVES.....	6-9
6.4 DESIGN RECOMMENDATION.....	6-10
6.5 COMPARISON OF ENHANCED DESIGN ALTERNATIVE II AND VIABILITY ASSESSMENT DESIGN	6-14
7. RECOMMENDATIONS AND CONCLUSIONS.....	7-1
7.1 RECOMMENDED DESIGN	7-1
7.2 MAJOR CONSIDERATIONS OF THE RECOMMENDED DESIGN.....	7-2
7.3 RECOMMENDATIONS FOR OPTIMIZATION OF THE RECOMMENDED DESIGN	7-5
7.4 CONCLUSIONS	7-7
8. REFERENCES.....	8-1
8.1 DOCUMENTS CITED	8-1
8.2 CODES, STANDARDS, AND REGULATIONS	8-12
8.3 PROCEDURES	8-13
APPENDIX A - LICENSE APPLICATION DESIGN SELECTION PROJECT DIRECTION AND GUIDANCE.....	A-1
APPENDIX B - LICENSE APPLICATION DESIGN INTEGRATION GROUP GUIDANCE AND DIRECTION.....	B-1
APPENDIX C - OTHER CONSIDERATIONS	C-1
APPENDIX D - GLOSSARY	D-1

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FIGURES

	Page
ES-1. Comparison of Key Design Attributes Between Enhanced Design Alternative II and the Viability Assessment Design.....	x
1-1. License Application Design Selection Team Organization	1-5
3-1. License Application Design Selection Two-Phase Process	3-8
3-2. Objectives Hierarchy for Phase I Evaluation Criteria	3-9
3-3. Objectives Hierarchy for Phase II Evaluation Criteria.....	3-10
4-1. Waste Packages Distributed by Waste Package Condition.....	4-22
4-2. Waste Packages Distributed by Thermal Output	4-22
4-3. Waste Packages Distributed by Radionuclide Content	4-23
4-4. Mixed Waste Package Distribution.....	4-23
4-5. Regionally Tailored Waste Package Distribution	4-24
4-6. Low Thermal Load Versus Viability Assessment Load	4-24
4-7. Postclosure Ventilation, Bow Tie Concept	4-25
4-8. Postclosure Ventilation, Triangle Concept.....	4-25
4-9. Open-Loop Postclosure Ventilation	4-26
4-10. Vertical Borehole Emplacement	4-26
4-11. Horizontal Borehole Emplacement	4-27
4-12. Trench Emplacement.....	4-27
4-13. Alcove Emplacement	4-28
4-14. Short Cross-Drift Emplacement	4-28
4-15. Viability Assessment Design	4-29
4-16. Viability Assessment Design with Options.....	4-29
4-17. Ceramic Coating on Waste Package	4-30
4-18. Typical Backfill Over Waste Package	4-30
4-19. Drip Shield Under Backfill	4-31
4-20. Drip Shield Over Backfill	4-31
4-21. Typical Pressurized-Water Reactor Fuel Assembly.....	4-32
4-22. Consolidated and Canistered Fuel Rods in Waste Package	4-32
4-23. Concept of Ground Support Maintenance.....	4-33
4-24. Different Drift Diameters	4-33
4-25. Point Load and Line Load Configurations	4-34
4-26. Waste Package with Dual Corrosion-Resistant Materials.....	4-34
4-27. Richards Barrier	4-35
4-28. Diffusive Barrier Under Waste Package	4-35
4-29. Getter Under Waste Package.....	4-36
4-30. Individually Canistered Fuel Assemblies.....	4-36
4-31. Canister with Multi-Fuel Assemblies.....	4-37
4-32. All Fuel Assemblies in a Single Canister.....	4-37
4-33. Two Filler Options	4-38
4-34. Concrete Ground Support System.....	4-38

FIGURES (Continued)

	Page
4-35. Steel Set Ground Support System	4-39
4-36. Welded Wire Fabric Mesh Ground Support System.....	4-39
4-37. Grouted Rock Bolt Ground Support System.....	4-40
4-38. Near Field Rock Treatment Concept.....	4-40
4-39. Different Waste Package Spacings for Higher Thermal Load	4-41
5-1. Location of Upper and Lower Emplacement Levels within the Principal Rock Stratigraphic Units at Yucca Mountain	5-63
5-2. Waste Package for Enhanced Design Alternative I.....	5-63
5-3. Drip Shield Over Waste Package	5-64
5-4. Enhanced Design Alternative I Layout	5-64
5-5. Temperature and Relative Humidity Histories for Representative Waste Packages Used in the Corrosion Calculations for Enhanced Design Alternative I.....	5-65
5-6. Temperature Histories for Two Representative Waste Packages in Enhanced Design Alternative I	5-65
5-7. Enhanced Design Alternative I 10,000 Year Total Dose Rate History.....	5-66
5-8. Enhanced Design Alternative I One Million Year Total Dose Rate History	5-66
5-9. Enhanced Design Alternative II Layout.....	5-67
5-10. Extent of Boiling Fronts for Enhanced Design Alternative II.....	5-67
5-11. Temperature and Relative Humidity Histories for Representative Waste Packages Used in the Corrosion Calculations for Enhanced Design Alternative II (Without Aging)	5-68
5-12. Temperature Histories for Two Representative Waste Packages in Enhanced Design Alternative II (Without Aging)	5-68
5-13. Enhanced Design Alternative II 10,000 Year Total Dose Rate History	5-69
5-14. Enhanced Design Alternative II One Million Year Total Dose Rate History.....	5-69
5-15. Waste Package for Enhanced Design Alternative IIIb	5-70
5-16. Enhanced Design Alternative III Layout	5-70
5-17. Line-Loading for Enhanced Design Alternative III	5-71
5-18. Temperature and Relative Humidity Histories for Representative Waste Packages Used in the Corrosion Calculations for Enhanced Design Alternative III.....	5-71
5-19. Temperature Histories for Two Representative Waste Packages in Enhanced Design Alternative III.....	5-72
5-20. Enhanced Design Alternative IIIa 10,000 Year Total Dose Rate History	5-72
5-21. Enhanced Design Alternative IIIa One Million Year Total Dose Rate History.....	5-73
5-22. Enhanced Design Alternative IIIb 10,000 Year Total Dose Rate History	5-73
5-23. Enhanced Design Alternative IIIb One Million Year Total Dose Rate History	5-74
5-24. Enhanced Design Alternative IV Layout	5-74
5-25. Waste Package for Enhanced Design Alternative IV.....	5-75
5-26. Integral Filler in Waste Package	5-75

FIGURES (Continued)

	Page
5-27. Temperature and Relative Humidity Histories for Representative Waste Packages Used in the Corrosion Calculations for Enhanced Design Alternative IV.....	5-76
5-28. Temperature Histories for Two Representative Waste Packages in Enhanced Design Alternative IV	5-76
5-29. Enhanced Design Alternative IV 10,000 Year Total Dose Rate History.....	5-77
5-30. Enhanced Design Alternative IV One Million Year Total Dose Rate History	5-77
5-31. Enhanced Design Alternative V Layout.....	5-78
5-32. Temperature and Relative Humidity Histories for Representative Waste Packages Used in the Corrosion Calculations for Enhanced Design Alternative V	5-78
5-33. Temperature Histories for Two Representative Waste Packages in Enhanced Design Alternative V.....	5-79
5-34. Enhanced Design Alternative V 10,000 Year Total Dose Rate History	5-79
5-35. Enhanced Design Alternative V One Million Year Total Dose Rate History	5-80
5-36. Drip Shield Failure Distribution for Those Drip Shields that Experience Seeps.....	5-80
5-37. Waste Package Failure Distribution for Those Waste Packages that Experience Seeps.....	5-81
6-1. Enhanced Design Alternative II and Viability Assessment Temperature/Relative Humidity Corrosion Susceptibility Comparison	6-17
6-2. Dose Rate at 20 km, Central Estimate.....	6-17

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TABLES

	Page
O-1. Phase I Evaluation Criteria.....	O-3
O-2. Phase II Evaluation Criteria	O-7
O-3. License Application Design Selection Enhanced Design Alternatives—Design Values.....	O-13
O-4. Enhanced Design Alternative Ranking Against Evaluation Criteria	O-20
O-5. Principal Results of Analysis of Enhanced Design Alternatives	O-22
O-6. Comparison of Enhanced Design Alternative II and Viability Assessment Design	O-24
 4-1. References Reviewed by the License Application Design Selection Core Team to Address Design-Related Concerns of Stakeholder and Oversight Groups	 4-2
4-2. Origins of Design Alternatives.....	4-4
4-3. Origins of Design Features.....	4-5
 5-1. Summary of Design Feature and Design Alternative Evaluations.....	 5-4
5-2. Candidate Enhanced Design Alternatives Worksheet.....	5-14
5-3. License Application Design Selection Enhanced Design Alternatives Identified at the End of Phase I (February 4, 1999)	5-20
5-4. License Application Design Selection Enhanced Design Alternatives— Design Values	5-39
5-5. Cost Estimate for Enhanced Design Alternative I	5-44
5-6. Cost Estimate for Enhanced Design Alternative II	5-47
5-7. Cost Estimates for Enhanced Design Alternatives IIIa and IIIb	5-53
5-8. Cost Estimate for Enhanced Design Alternative IV.....	5-57
5-9. Cost Estimate for Enhanced Design Alternative V	5-61
5-10. Cost Estimate for the Viability Assessment Design.....	5-62
 6-1. Summary Evaluations	 6-10
6-2. Principal Results of Analysis of Enhanced Design Alternatives	6-11
6-3. Comparison of Enhanced Design Alternative II and Viability Assessment Design	6-15
 B-1. Policy Guidance Issues Discussed by the License Application Design Integration Group.....	 B-1
 D-1. Metal Alloy Nomenclature.....	 D-4

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ACRONYMS

CFR	U.S. Code of Federal Regulations
CRWMS	Civilian Radioactive Waste Management System
DA	design alternative
DF	design feature
DOE	U.S. Department of Energy
EDA	enhanced design alternative
EIA	Energy Information Administration
FR	Federal Register
KTI	key technical issue
LADS	License Application Design Selection
M&O	Management and Operating Contractor
MGR	Monitored Geologic Repository
MPC	multi-purpose canister
MRS	monitored retrievable storage
MTHM	metric tons of heavy metal
NRC	U.S. Nuclear Regulatory Commission
NWTRB	Nuclear Waste Technical Review Board
PWR	pressurized-water reactor
TBV	to be verified
TSPA	total system performance assessment
YMP	Yucca Mountain Site Characterization Project

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O. OVERVIEW

O.1 BACKGROUND AND GOALS OF THE STUDY

During the preparation of the Viability Assessment (DOE 1998b), the U.S. Department of Energy (DOE) directed the Management and Operating Contractor (M&O) for the Civilian Radioactive Waste Management Program to conduct a formal study of alternative design concepts for a potential geologic repository for spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nevada (Dyer 1998). The study, called the License Application Design Selection (LADS) project, was initiated in July 1998, and resulted in the development and submission of the report in April 1999.

The focus of this study was on the engineered aspects of a potential repository that would complement the natural system of the Yucca Mountain site. For the vast majority of the radionuclides that would potentially be emplaced in a repository, the Yucca Mountain site alone (the natural barrier system) appears to be capable of containing them and preventing any transport to the accessible environment. A small fraction of the radionuclides appear to be mobile and, under some circumstances, could move out of the potential repository if they are exposed to liquid water. This concern can be mitigated by use of an engineered barrier system to limit the exposure of these radionuclides to the small amount of water moving through the unsaturated zone at the site. A major focus of the repository design process is to identify a sufficient set of engineered barriers to accomplish this task.

The goal of the LADS project was to develop and evaluate a diverse range of possible repository designs that work well in concert with the Yucca Mountain site and to arrive at a recommended initial conceptual design. This design will be the starting point for the possible Site Recommendation and License Application. DOE will then review the design recommendation and select a design concept for further consideration. Because the design carried forward into the possible Site Recommendation and License Application is a joint decision responsibility, both M&O and DOE management provided input to the decision methodology and implementation.

Since the LADS recommendation is a conceptual design, the various design elements considered during the study were conceptual in nature; for example, the study focused on the general design of the waste package (the type and arrangement of materials) rather than on the precise dimensions and fabrication techniques. More detailed design activities will occur following the LADS project and prior to the possible Site Recommendation and License Application. By keeping the evaluations at a conceptual design level, the LADS team was able to consider a wide range of design options despite the differences in data available for various design elements.

The development of the License Application design will necessarily be an iterative process, involving newly acquired scientific information, evolution of performance assessment models, and design evolution, starting from the recommended design.

O.2 DESIGN PROCESS

The LADS study was a conceptual design process guided by general principles of decision-making. Unlike many decision analysis applications that focus on a formal evaluation of a well-defined set of alternatives, the primary emphasis in the LADS study was on the creative development of alternative designs that continued to evolve throughout the course of the project as the ongoing analysis provided additional insights. The LADS project developed a process intended to promote creative design work, and to make good use of the professional engineering judgment and conceptual design experience of the participants in the process. The process of making a selection from among the enhanced design alternatives (EDAs) was accomplished using an iterative, documented approach based on consensus of the LADS core team and M&O management.

The LADS process benefited from the review and comment by multiple review groups, including the Nuclear Waste Technical Review Board, the Repository Consulting Board, the Total System Performance Assessment (TSPA) Peer Review Panel, and the Design Alternatives Review Panel, which was specifically established to comment on the LADS process. High-level M&O and DOE management oversight and direction were provided by the License Application Design Integration Group.

The LADS decision process consisted of two phases, with the first phase resulting in the alternatives to be evaluated and the second phase resulting in a design recommendation. The purpose was to arrive at a repository design that could be carried forward into the possible Site Recommendation and License Application. Values were specified through an objectives hierarchy and developed to identify the fundamental objectives—the evaluation criteria—for evaluating the design alternatives (DAs) and design features (DFs) in Phase I and the EDAs in Phase II. The sets of criteria for the two phases were tailored to the scope of each phase. Alternatives to be evaluated in Phase II were created from the Phase I process, including both the identification of objectives and evaluation of the components of designs (i.e., the DAs and DFs). Following design development and refinement, the EDAs were evaluated against the evaluation criteria and a final design was recommended. This is consistent with the value-focused approach of first considering the objectives and values that are desired (the evaluation criteria), developing a diverse set of alternatives that have the potential to meet these objectives, and evaluating the alternatives and selecting from among them.

O.2.1 Phase I—Evaluation of Independent Design Alternatives and Design Features

In Phase I, a number of DAs were considered in their simplest form; in that phase, the goal was to consider a basic design concept (e.g., low thermal load design) without additional DFs to enhance its performance. Likewise, the DFs were evaluated as single changes to the Viability Assessment design, without considering the potential effects a DF might have if added to a different DA or in combination with other DFs. These Phase I definitions and associated analyses were intended to provide comparative information of the DAs and DFs to help in evaluating them against the Phase I evaluation criteria. By considering all of the DAs and DFs using the same assumptions, it was possible to compare and evaluate those DAs and DFs on an essentially equivalent basis. The Phase I activities concluded with the identification of a candidate set of EDAs, design concepts that had been enhanced by the inclusion of multiple DFs.

O.2.1.1 Phase I Evaluation Criteria

The design process used a value-focused approach, in which the objectives or values (to be used as evaluation criteria) are identified first so that the alternatives can be created to meet those objectives. This process is intended to lead to the identification of alternatives that are consistent with the objectives, as well as to ensure that the fundamental objectives are met in the selection of one alternative. The criteria identified for Phase I consisted of both quantitative measures (e.g., postclosure performance and cost) and more qualitative measures (e.g., assurance of safety and engineering acceptance). The qualitative measures were scored on scales of 1 to 5, which were defined relative to the performance of the Viability Assessment design (assigned a level of 3 for comparison). The set of Phase I evaluation criteria is shown in Table O-1.

Table O-1. Phase I Evaluation Criteria

Criterion	Relevant Factors
Postclosure Performance	Peak dose within 10,000 years and 1 million years
Preclosure Performance	Effects on probability and consequences of operational incidents
Assurance of Safety	Uncertainties in postclosure performance, and potential to reduce them by the time of construction and closure
Engineering Acceptance	Ease of demonstrating postclosure function, regulatory/engineering precedents, availability of qualified data by the time of the possible License Application, constructability with proven methods
Construction/Operations/Maintenance	Impacts on worker radiation safety and industrial safety; on reliability, availability, maintainability, and inspectability of manufactured and constructed items; on throughput capability; and on the ability to perform performance confirmation activities
Schedule	Impacts on the Viability Assessment schedule for site characterization, design (if approved), licensing, and construction
Cost	Difference in total cost from the Viability Assessment design
Environmental Considerations	New environmental considerations relative to the Viability Assessment design

O.2.1.2 Identification and Evaluation of Candidate Design Elements

A second important step in Phase I was the identification of fundamental design elements that could be combined to produce the alternative repository concepts for evaluation. These design elements are:

- **DAs**—Each DA represents a fundamentally different conceptual design for the potential repository and, potentially, could stand alone as the repository design concept for the License Application. DAs are distinguished from DFs (described below) by their complexity and the number of attributes involved. DAs, while not mutually exclusive, represent diverse and independent methods of accomplishing the repository mission—safe disposal of spent nuclear fuel and high-level radioactive waste. One example of a DA is a repository designed to use continuous natural ventilation to remove heat and moisture from the area of the waste packages after the potential repository has been closed.

- **DFs**—A DF is a particular element or attribute of a repository that could be added to any DA to enhance its performance. An individual DF may represent a discrete concept, such as use of shielded waste packages, or a continuous range of values of some aspect of the potential repository design, such as spacing of the waste emplacement drifts. DFs can be added to any DA singly or in combination, although the compatibility of different DAs and DFs varies.

The LADS team drew on a number of sources in developing the set of DAs and DFs to be considered in Phase I. Some of the sources were:

- **Previous analyses**—A preliminary list of DAs and DFs, drawn from previous work by the program, was included in the Viability Assessment (DOE 1998b, Vol. 2, Section 8.2.5). These were reviewed and modified by the LADS team and senior DOE and M&O management to provide a starting point for analysis.
- **Stakeholder and independent oversight groups**—A number of outside groups have identified issues concerning the potential repository design and, in some cases, have suggested specific options for consideration. Sources of information included Nuclear Waste Technical Review Board reports, correspondence, and personal communications; U.S. Nuclear Regulatory Commission key technical issue reports; and reports by the University of Nevada-Reno and the Nye County Nuclear Waste Repository Project Office.
- **Internal review groups**—These included the Repository Consulting Board and the TSPA Peer Review Panel.

A total of eight DAs, including the Viability Assessment design, were identified for more detailed analysis. A total of 22 DFs were identified.

DAs identified for more detailed analysis (see Section 4.3) included:

- Tailored waste package spatial distribution
- Low thermal load design
- Continuous postclosure ventilation design
- Enhanced access design
- Modified waste emplacement mode design
- Viability Assessment design
- Viability Assessment design with options
- Modular design/phased construction

DFs identified for more detailed analysis (see Section 4.4) included:

- Ceramic coatings
- Drip shields
- Backfill
- Aging and blending of waste
- Continuous preclosure ventilation
- Rod consolidation

- Timing of repository closure
- Maintenance of underground features and ground support
- Drift diameter
- Drift spacing, waste package spacing
- Waste package self-shielding
- Waste package corrosion-resistant materials (metal and ceramic)
- Richards Barrier
- Diffusive barrier under the waste package
- Getter under the waste package
- Canistered assemblies
- Additives and fillers
- Ground support options
- Near field rock treatment during construction
- Surface modifications
- Repository horizon elevation
- Higher thermal loading

These DAs and DFs were subjected to engineering analysis and evaluation against the set of criteria established for use in this phase. The intent of this evaluation was to provide the designers with insights into the relative strengths and weaknesses of the components that could be used in assembling the EDAs. The evaluations against all of the criteria except postclosure performance were made by the lead design engineers assigned to each DA and DF. The overall evaluations for each criterion were based on responses to detailed questions that provided the documented technical basis for the judgments.

Postclosure performance was evaluated by the performance assessment group of the M&O. Since the DFs could not be evaluated in terms of their contribution to long-term repository performance without being associated with an overall repository concept, they were evaluated as additions to the Viability Assessment design. The TSPA model used for the Viability Assessment was adapted, to the extent possible, to perform this analysis. In order to evaluate a large number of DAs and DFs in a short time, the performance assessment organization calculated a central estimate of performance (using a single value of most of the variables in the TSPA model), instead of calculating a range of results reflecting the uncertainties. The uncertainty in the performance of each of the DAs and DFs was estimated separately in a qualitative measure termed "assurance of safety," which reflected the magnitude of those uncertainties and the expected ability to reduce them by the time of a possible License Application. Improved performance assessment models, based on updated scientific information, will be used in future development of the design.

O.2.1.3 Development of Enhanced Design Alternatives

The Phase I activities concluded with the identification of a candidate set of EDAs, design concepts that had been enhanced by the inclusion of multiple DFs.

EDAs are conceptual designs of the repository system that include the set of features needed to provide acceptable overall performance and that could serve as the basis for the possible Site Recommendation and License Application. The EDAs were developed by taking into account

both the evaluation criteria considered in Phase I and the new criteria they would be evaluated against in Phase II. The EDAs were not subject to the constraints associated with Phase I, and could be developed based on any combination of DAs and DFs. The designations of design concepts as either a "DA" or "DF," which helped in the organization of the effort in Phase I, were not given any significance in the EDA development process. Hence, the basic elements of two DAs could be combined if deemed appropriate, or multiple DFs could be associated with any number of DAs.

The major objectives of the EDA development process were to: 1) arrive at a reasonable number of EDAs for further detailed evaluation, 2) build up EDAs likely to be evaluated highly against the Phase II evaluation criteria (described below), and 3) develop a diverse set of EDAs that, as a group, represents an appropriate range of design types. The purpose was to provide the decision makers a meaningful range of choices.

To accomplish these objectives, a process was designed to build up EDAs with a high potential for success, rather than to eliminate possible design combinations. This process focused on identifying a set of diverse, successful EDAs, not on screening and eliminating possible combinations of DAs and DFs. This approach reflects the fact that to consider all possible combinations would be unmanageable because there are so many elements that could be used in a repository design. The LADS process was intended to avoid identifying an EDA that would not rate well against the Phase II evaluation criteria. The information developed for the DAs and DFs, in addition to other information developed for the Yucca Mountain Site Characterization Project, was used to the maximum extent possible. Engineering judgment based on past experience, however, was also essential for the EDA development and selection process.

O.2.1.4 Criteria for Evaluating Enhanced Design Alternatives in Phase II

To guide the development of the EDAs and to provide a basis for discriminating among them, a revised set of criteria was prepared for evaluation of the EDAs. First, the LADS team determined that for an EDA to warrant further evaluation, it must have a calculated postclosure performance level that would meet regulatory requirements. Since the standard for Yucca Mountain has not yet been issued by the U.S. Environmental Protection Agency, the evaluation used, as a proxy, a maximum radiation dose value of 25 mrem/yr in the first 10,000 years to an average member of a critical group at a distance of 20 km from the potential repository. This was consistent with the U.S. Nuclear Regulatory Commission's proposed site-specific regulation for licensing a Yucca Mountain repository (see 64 FR 8640).

To arrive at the Phase II criteria for evaluating the EDAs that passed this initial screening criterion, some of the Phase I criteria were consolidated and simplified, and some new criteria were added. The Phase II criteria reflect the fact that the EDAs are more complete conceptual repository systems with properties that would not be apparent in the simpler DAs and DFs considered in Phase I. For example, all of the EDAs included provisions to provide defense in depth, a measure associated with the number and diversity of barriers in the potential repository. Another important Phase II criterion applicable to a fully developed EDA is "flexibility," which reflects the ability of a design to remain viable or adaptable in the face of possible future programmatic or regulatory changes.

For purposes of consistent analysis, this study used the Viability Assessment assumption that spent nuclear fuel and high-level radioactive waste equivalent to 70,000 metric tons of heavy metal (MTHM) would be received and emplaced in the potential repository.

Most of the evaluation criteria included several submeasures that helped define them further. In many cases, these submeasures simply represented criteria used in Phase I. A complete list of the Phase II evaluation criteria is shown in Table O-2.

Table O-2. Phase II Evaluation Criteria

Criterion	Main Relevant Factors
Screening--meets regulatory requirements	Peak annual dose rate within 10,000 years of 25 mrem/yr to the average member of a critical group at 20 km from the potential repository
Performance Demonstrability	<ul style="list-style-type: none"> • Time to 25 mrem/yr dose • Estimated level and timing of the peak dose rate in 1 million years • Ratio of 25 mrem/yr to peak dose rate in 10,000 years • Degree of defense in depth • Uncertainties in factors affecting postclosure performance and the ability to mitigate them by the time of a possible License Application • Engineering acceptance • Environmental considerations
Construction/operations/maintenance	<ul style="list-style-type: none"> • Worker safety • Constructability • Operations • Maintainability • Handling logistics • Performance confirmation • Off-normal events
Flexibility	<ul style="list-style-type: none"> • Increased disposal capacity beyond 70,000 MTHM (to 87,000 or 105,000 MTHM, if authorized) • Preclosure period (10 years after emplacement; 100 years; 300 years) • Receipt of 5-year-old commercial spent nuclear fuel • Design changes (hot ↔ cold; blending; backfill) • Unanticipated natural features or findings
Cost/schedule	Time and costs (total and net present value) required for site characterization and licensing, construction, operations, monitoring, and closure

O.2.1.5 Enhanced Design Alternative Development Workshop

The initial set of EDAs was developed during a 10-day workshop held January 4 to 15, 1999. The workshop participants included the LADS team, lead design engineers for the DAs and DFs, and performance assessment leads. Observers from the M&O, DOE, Nuclear Waste Technical Review Board, U.S. Nuclear Regulatory Commission, and the TSPA Peer Review Panel were also present. The workshop was structured to provide a focus on the decision-making body (the LADS core team) and to encourage the exchange of ideas. Participation was encouraged from the LADS team, while observers were provided ample opportunities to ask questions and share their perspectives.

To facilitate the development of a range of diverse EDAs, the participants in the workshop were divided into three working groups. These groups focused on three broad classes of designs: high-temperature designs, low-temperature designs, and designs allowing enhanced human access. This division reflected two major dimensions on which the Viability Assessment design could be changed: the temperatures in the potential repository caused by the heat emitted by the decay of the radioactive waste, and the ease of human access to the drifts containing the waste. These two dimensions represent two significant differences in design philosophy.

Temperatures in the Potential Repository—Spent nuclear fuel and high-level radioactive waste emit heat associated with radiation. Designing the potential repository to limit the waste package surface temperature and to keep temperatures in much or all of the repository rock below the boiling point of water could improve waste package performance and reduce uncertainties resulting from changes in the repository environment caused by the heat from the waste. Alternatively, careful management of the heat could dry out the rock around the emplacement drifts for an extended period and thereby improve performance and reduce uncertainty by reducing or eliminating the seepage of water into the drifts during that time.

Ease of Human Access—In one approach, all needed operations in the repository drifts, with waste present, can and should be performed using remote equipment, as in the Viability Assessment design. Alternatively, provisions for human access to drifts containing waste could be required in at least some situations, such as unexpected events that might require human inspection to determine what measures need to be taken.

The Viability Assessment design represents a high-temperature design that does not allow direct human access to the loaded drifts. The creation of working groups to focus on designs that differ significantly from the Viability Assessment design in these two important dimensions was intended to ensure that the resulting set of alternatives would reflect significant differences in philosophy and, therefore, would represent more than just minor variations on the Viability Assessment design. This helped provide the diversity that was a key goal of the EDA development process.

In developing alternative designs, both the high-temperature and low-temperature groups were allowed to consider enhanced access options if they wished, while the enhanced access group was free to consider both high-temperature and low-temperature options. Each working group was expected to become an advocate for the designs it developed and to defend these designs in the general sessions of the workshop in order to promote a thorough airing of the expected differences of opinion regarding the merits of various design concepts.

The initial sessions of the working groups produced a total of 23 candidate-EDA concepts. Subsequent discussions in the full workshop and in additional working group meetings resulted in the selection of eight candidate EDAs. These final eight were chosen by a consensus of the LADS core team. These eight EDAs included two low-temperature designs, three high-temperature designs, and three designs with enhanced human access.

O.2.2 Phase II—Refinement and Evaluation of Enhanced Design Alternatives

O.2.2.1 Selection of Final Set of Enhanced Design Alternatives for Phase II

Following completion of the EDA workshop, the eight candidate EDAs developed at the workshop were reviewed and refined by the LADS core team to arrive at five EDAs to be analyzed in Phase II (referred to as EDAs I through V). Before doing so, the core team considered a number of potentially significant issues that had been determined to be important factors during Phase I:

- Keeping the temperature of the spent-fuel cladding below 350°C to avoid possible breach of the cladding by creep rupture. The pinholes from such breaches could allow water to contact the fuel pellets after the waste packages are breached. If the waste package is also breached during the thermal pulse (in this case while spent nuclear fuel temperatures are above about 200°C), pinholes and cladding can result in more extensive clad failure due to expansion of waste as it oxidizes.
- Being able to close the potential repository as early as 50 years after the start of waste emplacement.
- Maintaining thermal independence of the emplacement drifts (defined as keeping the centers of the pillars between the drifts below the boiling point of water).
- Allowing personnel access (defined as the ability to gain access to the emplacement drifts to deal with off-normal and design basis events).

Based on consultation with the License Application Design Integration Group, these issues were divided into three categories for the purpose of developing the EDAs:

- The EDA designs should strive not to exceed the 350°C cladding temperature limit and be able to close after 50 years unless there are clear benefits to not doing so. Management should be informed before these limits are exceeded.
- Thermal independence of drifts should be considered for inclusion in a design, but it would not be specified as a goal or requirement for all of the EDAs.
- Personnel access is a requirement for all designs, and management was to be alerted if it could not be met. To guide the further development of the EDAs, management decided that every EDA should include provisions for personnel access that would ensure a capability to respond to operational off-normal and design basis events, including that access to the drifts be feasible within four weeks.

Given these considerations and the Phase II evaluation criteria, the core team reconsidered the eight EDAs. With better-defined requirements, it was decided that personnel access to the emplacement drifts could be part of any of the EDAs and could be accomplished principally through the use of blast cooling and portable shielding. Preliminary calculations of waste package radiation levels indicated that the requirements could be met in this way. This allowed the team to consider whether to eliminate some elements of the enhanced access designs (such as

emplacement of waste packages in trenches or boreholes), whose primary function was to provide shielding.

To ensure that all of the EDAs to be analyzed in Phase II were on an essentially equivalent basis, an attempt was made to use common assumptions among the designs wherever possible. For example, the same waste package materials were used unless an integral aspect of the design called for different materials. To improve waste package performance, most of the EDAs used a waste package with a 2-cm layer of corrosion-resistant Alloy-22 protecting a 5-cm inner structural shell of stainless steel 316L. In addition, to reduce uncertainty in waste mobilization and transport, a steel ground support and invert system for the repository emplacement drifts was used, rather than the concrete liner used in the Viability Assessment design. The analyses of the EDAs used the waste stream assumptions from the Viability Assessment, including emplacement of 63,000 MTHM of commercial spent nuclear fuel and a total of 7,000 MTHM-equivalent of DOE spent nuclear fuel and high-level radioactive waste.

The analysis of the Viability Assessment design indicated that additional defense-in-depth measures are desirable. Analysis of the DFs/DAs in Phase I of the LADS effort identified drip shields over the waste packages as a particularly promising way to enhance defense in depth. To simplify the comparison of EDAs, a common drip shield design (using the titanium alloy grade 7 [Ti-7]) was specified as the placeholder for defense in depth across all of the designs. Other DFs/DAs judged to have potential for possible defense-in-depth benefits were identified during Phase I after the consideration of such issues as design compatibility, operability, licensability, performance uncertainties, and cost. These DFs/DAs are listed below. The list represents a menu of additional enhancements that could be added to the design during future refinement, depending on the degree of defense in depth desired.

- Ceramic coating on waste package
- Drip shield (metal, monolithic ceramic, or ceramic-coated metal)
- Backfill (calcite, quartz, or tuff)
- Filler inside the waste package
- Dual corrosion-resistant materials waste package
- Richards Barrier
- Canistered assemblies
- Trench with lid

Once these common assumptions were adopted, the major remaining dimension for diversity in the set of EDAs selected for evaluation was the choice of thermal management strategies. The difference was whether (and how) the heat emitted by the waste would be used or controlled to enhance the performance objectives or reduce uncertainties. All of the EDAs adopted goals on the temperatures of the spent nuclear fuel cladding and the drift walls.

The EDAs selected for evaluation differed significantly in the choice of whether to control the effects of heat even more or to designate a positive use for the heat. To provide a broad set of approaches, the EDAs spanned a range of temperature goals for the temperatures at the waste package surface, drift wall, and centerline between the drifts. For example, EDA I sought to keep all of the rock in the potential repository below the boiling point of water in order to limit the complications arising from boiling large quantities of the water in the rock of the potential

repository region. In contrast, EDA V sought to keep the entire repository area above the boiling point of water (within the constraints mentioned above) as long as possible. This could keep the waste packages hot and dry, which, in turn, would prevent corrosion for an extended period.

The major features of the five EDAs represented choices about how to achieve the specified temperature goals. The main choices were:

Waste Package Size—Increasing the amount of spent nuclear fuel in a waste package increases its heat output. This axiom can affect the maximum temperatures reached by the fuel cladding, the waste package surface, and the nearby rock. Other factors being equal, smaller packages make it easier to meet thermal goals in and immediately around the waste packages. Using smaller packages increases the number and total cost of the waste packages, the number of handling operations (although the smaller packages may be somewhat easier to handle), and the length of the emplacement drifts required. EDA I used smaller waste packages than the other EDAs.

Blending—Commercial spent nuclear fuel assemblies arriving at the potential repository are expected to have a wide range of heat outputs. If the assemblies are loaded into waste packages as soon as they arrive, some waste packages may be loaded with mostly hot assemblies and others with mostly cool assemblies. This can lead to a wide variation in the heat outputs of different waste packages, which can, in turn, cause localized hot or cool spots in the emplacement drifts. This could introduce potential performance issues and complications in analyzing the repository performance. Blending involves holding some of the hotter fuel assemblies as they arrive until cooler assemblies are available. In this way, hotter and cooler assemblies can be combined in a waste package to reduce the variability in the overall heat output and also in nuclear criticality potential of the different packages. Blending reduces the problems caused by wide variations in heat output, but would require some amount of holding capacity. It would also increase the complexity of the waste handling operations. (The Viability Assessment design and EDAs IIIa, IIIb, and IV use limited blending [i.e., spent nuclear fuel assemblies that exceed a specified thermal output or nuclear criticality measure would be placed in smaller packages containing fewer assemblies to limit the total heat output or nuclear criticality measure of those packages].) The analysis of blending as a DF indicated that an increase in the planned capacity of the pool in the fuel receipt facility could allow sufficient blending to reduce the variation in waste package heat outputs to 20 percent above the average heat output of the waste packages containing fuel from pressurized-water reactors (PWR). This level of blending was assumed by the three EDAs that incorporate blending.

Waste Package Spacing—The closer the waste packages are placed to each other in the emplacement drifts, the more they are influenced by the heat emitted by their neighbors. This can increase the temperatures in and around the waste packages, and the overall heating of the rock around the drifts. If waste packages have high heat outputs, they may have to be spaced so far apart that they must be analyzed as separate point sources of heat (called a “point load”). Alternatively, in the “line load” approach, waste packages are placed close together so that heat can be transferred from package to package, primarily by thermal radiation. While this increases temperatures in and around the packages, it tends to even out the effects of differences in heat outputs among the packages. It also simplifies the analysis by allowing the packages in a drift to be treated as a uniform line source of heat instead of a large number of separate, non-uniform

sources. By greatly reducing the spacing between waste packages, the line-load approach could use fewer drifts to contain the same waste inventory. Fewer drifts means less excavation. Because of these advantages, all of the EDAs sought to use line loading; all but EDA I were able to do so and still meet their other thermal goals.

Drift Spacing—Other factors being equal, the closer the waste emplacement drifts, the hotter the rock pillars between them can get, and the more the heat from one drift affects the temperatures in its neighbors. If the drift spacing is close enough, all of the rock for some distance around the entire repository area will be heated above the boiling point of water. This should produce a “thermal umbrella” above the potential repository that could keep water out of the drifts for an extended period of time. Close spacing also reduces the total amount of repository area needed for disposal of any given amount of waste. Alternatively, spreading the drifts far enough apart so the centers of the pillars between them do not exceed the boiling point of water is expected to allow the water (infiltrating from the surface or mobilized from the pores of the rock by the heat from the waste) to drain around the drifts. The EDAs selected for evaluation represent a wide range of drift spacings. The combination of spacing between the drifts and the spacing of waste packages within the drifts determines the overall areal mass loading of the potential repository design (i.e., the total mass of spent nuclear fuel emplaced per acre of repository space). (The areal mass loading is usually stated in MTHM/acre.) The five EDAs have a wide range of drift spacings and areal mass loadings.

Aging and Ventilation—The heat output of spent nuclear fuel and high-level radioactive waste declines as the waste gets older. Active ventilation of the loaded emplacement drifts can remove a substantial fraction of the heat emitted by the waste in the period before the potential repository is closed, making it easier to limit the postclosure peak temperatures in and around the waste packages. The Viability Assessment design includes a very low ventilation rate designed for radiation monitoring rather than thermal management. Because all of the EDAs either place the waste packages much closer together or have lower temperature goals than the Viability Assessment design, all require substantially higher ventilation rates to keep temperatures within the design limits. These higher ventilation rates involve the construction of additional ventilation shafts and drifts, equipment and power sources designed to achieve higher reliability for many years, and higher operating costs during the open period of the potential repository. While the initial analysis of candidate EDAs during the Phase I workshop assumed that some aging before emplacement could be required to meet thermal management objectives, subsequent analysis showed that all of the EDAs could meet their thermal goals with ventilation and blending.

Considering these design options and the key elements of the eight EDAs from Phase I, the LADS team developed a set of five EDAs for detailed analysis. These evolved during Phase II. The characteristics of the EDAs scored and ranked at the end of Phase II are summarized in Table O-3.

O.2.2.2 Evaluation Using the Phase II Criteria

The final step was to perform comparative evaluations among the resulting five EDAs. It was first determined that all of the EDAs that made it to this last step were, in fact, feasible. That is, there is a reasonable probability that all of them can be constructed, licensed, and operated

Table O-3. License Application Design Selection Enhanced Design Alternatives—Design Values

Design Element	EDA I	EDA II	EDA III	EDA IV	EDA V
Thermal Goals					
• Cladding	350°C	350°C	350°C	350°C	350°C
• Waste package surface			Cools to 80°C before relative humidity reaches 90%		
• Drift wall	96°C	200°C	200°C	200°C	225°C
• Drift environment				Keep drifts dry for thousands of years	Keep drifts dry for several thousand years
• Pillar temperatures		Keep centers of pillars below boiling (96°C)			
• Other goals				Limit gamma dose at waste package surface to 200 mrem/hr	
Areal Mass Loading (MTHM/acre)	45	60	85	85	150
Area (acres) for 70,000 MTHM ¹	1,400	1,050	740	740	420
Line/Point Load	Point	Line	Line	Line	Line
Waste Package Size (PWR)	12	21	21	21	21
Drift Diameter (m)	5.5	5.5	5.5	5.5	5.5
Drift Spacing (m)	43	81	56	56	32
Preclosure Ventilation	50 years @ 2 to 10 m ³ /s	50 years @ 2 to 10 m ³ /s	50 years @ 2 to 10 m ³ /s	50 years @ 2 to 10 m ³ /s	50 years @ 2 to 10 m ³ /s
Waste package heat output at emplacement Maximum Average (PWR waste package)	20% blending used to reduce maximum 6.7 kW 5.6 kW	20% blending used to reduce maximum 11.8 kW 9.8 kW	Limited blending 18.0 kW 9.5 kW	Limited blending 18.0 kW 9.5 kW	20% blending used to reduce maximum 11.8 kW 9.8 kW
Waste Package Material	2-cm Alloy-22 over 5-cm stainless steel	2-cm Alloy-22 over 5-cm stainless steel	a) 2-cm Alloy-22 over 5-cm stainless steel b) 2-cm Alloy-22 over 1.5-cm Ti-7 over 4-cm stainless steel	30-cm carbon steel	2-cm Alloy-22 over 5-cm stainless steel
Fillers	No	No	No	Integral filler	No
Backfill	No	Yes	No	Yes	No
Drip Shield	Yes	Yes	Yes	Yes	Yes
Total Waste Packages	15,903	10,039	10,213	10,213	10,039

¹ Areas are calculated by dividing the commercial inventory (63,000 MTHM) by the areal mass loading and rounding to the nearest 10 acres; additional area will be required for perimeter drifts, maintenance drifts, and contingency areas.

within the appropriate programmatic and regulatory constraints. Then, the Phase II criteria were used to evaluate each of the EDAs separately. The following discussion summarizes the key features of the EDAs and principal results of the evaluation.

EDA I—Low-Temperature Design

This EDA was intended to reduce uncertainties about the performance of the potential repository by reducing the effect of the heat from the waste on the natural system of the potential repository. It was designed to keep all of the rock in the repository below the boiling point of water (96°C) at the potential repository elevation (1,070 m). This design was expected to reduce or avoid the need to develop performance assessment models to predict the effects of long periods of above-boiling conditions on the chemical, mechanical, and hydrologic properties of the rock. This could simplify the analysis of the behavior of the potential repository during the period when the waste is still emitting significant amounts of heat (thermal period). Reducing heat-induced alterations of the natural barriers should also reduce the uncertainties about performance in the very long term after the temperatures in the potential repository have returned to levels close to what existed before the waste was emplaced. The measures needed to keep the rock temperatures below the boiling point of water are also expected to minimize the amount of time that the waste packages are in an environment where they are particularly susceptible to corrosion. This environment appears when the temperatures are between about 85 and 125°C and the relative humidity is above 80 percent. The chemistry of the water is also a key factor in corrosion susceptibility.

Key Design Features—Thermal management features include:

- Relatively small waste packages (compared with other EDAs) to limit the heat output per package
- Some separation of the waste packages to reduce the drift wall temperatures
- Wider spacing of the drifts (45 m) than used in the Viability Assessment design
- Blending to reduce variation in waste package heat outputs
- Active ventilation for 50 years before closure

The key engineered barriers are the waste package (2 cm of Alloy-22 over 5 cm of stainless steel) and common drip shield (2 cm of Ti-7 in a self-supporting structure). This waste package configuration and this drip shield configuration are common to several of the other EDAs.

Principal Results of Evaluation—Results of evaluation indicated that for EDA I:

- The calculated peak 10,000-year radiation dose rate is 0.01 mrem/yr, an insignificant fraction of the screening level of 25 mrem/yr. The screening dose rate level is not reached until 290,000 years, well after the screening period of 10,000 years. The calculated peak dose rate of 85 mrem/yr occurs at 320,000 years. The 10,000-year dose rate is entirely due to an assumed juvenile failure of one waste package at 1,000 years.

- Maximum calculated drift wall temperature is 94°C, which allows waste packages to cool below the point of corrosion vulnerability within several hundred years.
- EDA I performs best in terms of engineering acceptance and uncertainties in performance.
- EDA I performs worst in terms of flexibility and cost.
- EDA I requires 60 percent more waste packages than the other EDAs, and more than twice the emplacement drift length, increasing the probability of accidents during construction and operation.
- EDA I requires 1,400 acres, most of the area that has been characterized to date.

EDA II–Hot Drifts, Cool Pillars Design

This EDA was intended to limit the heating of the drifts and surrounding rock so that a significant portion of the pillars between the drifts (at least 50 percent) remains below the boiling point of water. This was expected to allow water above the repository (both infiltration from the surface and water mobilized in the rock by the heat of the waste) to flow around the heated drifts and down through the cooler pillars. Allowing the rock in the immediate vicinity of the drifts to heat above the boiling point of water would create a region of hot, dry rock that could reduce seepage into the drifts as long as the thermal period lasts. This approach may reduce uncertainties in several ways. First, it limits the amount of rock that is subject to alteration by temperatures above boiling. Second, providing drainage paths around the drifts should prevent water from accumulating in fractures above the drifts and perhaps flowing back into drifts episodically (as may occur if almost all of the rock at the repository is above the boiling point of water). Third, it may allow the potential repository to be analyzed as a collection of independent drifts, without requiring analysis of the complex effects of heat over the entire repository area.

Key Design Features—Thermal management features include:

- Very wide drift spacing (81 m) to ensure that the central area of the pillars remains below boiling
- Close waste package spacing (line loading)
- Blending to reduce the variation in waste package heat outputs
- Active ventilation for 50 years before closure
- Backfill to prolong hot, dry conditions around the drip shield and waste package

The key engineered barriers are the waste package (2 cm of Alloy-22 over 5 cm of stainless steel) and common drip shield, with backfill covering the drip shield. The backfill provides added protection against rockfall and avoids temperature/humidity conditions conducive to aggressive crevice corrosion of Alloy-22.

Principal Results of Evaluation—Results of evaluation indicated that for EDA II:

- The calculated peak 10,000-year radiation dose rate is 0.007 mrem/yr, an insignificant fraction of the screening level of 25 mrem/yr. The screening dose rate level is not reached until 310,000 years, well after the screening period of 10,000 years. The calculated peak dose rate of 85 mrem/yr occurs at 620,000 years. The 10,000-year dose rate is entirely due to an assumed juvenile failure of one waste package at 1,000 years.
- Much of the pillar width always remains below the boiling point of water.
- EDA II was a good performer on licensability factors.
- EDA II introduces operational complexities due to addition of backfill.
- About 1,050 acres would be required, fitting within the upper emplacement level of the characterized area.
- EDA II has flexibility to be modified for higher or lower thermal goals.

EDA III—High Thermal Load Design

This design was considered to evaluate the effects of both the common waste package and an enhanced version in a relatively hot thermal environment similar to the Viability Assessment design. The thermal goals of EDA III were to limit the drift wall temperature to 200°C, limit the fuel cladding temperature to 350°C, and ensure that the waste package surface temperatures cool to below 80°C before the relative humidity at the waste package surface rises above 90 percent. The latter goal is to avoid combinations of humidity and temperature conducive to aggressive crevice corrosion of Alloy-22. Some drying out of the rock between the drifts is expected. The effect of creating a large region of hot, dry rock is the prevention of seepage into the drifts for as long as the thermal period lasts.

Key Design Features—Thermal management features include:

- Wide drift spacing (56 m, nearly double the Viability Assessment design spacing) to limit the effects of the heat from each drift on its neighbors; allows the cladding and drift wall goals to be met
- Close waste package spacing (line loading)
- Active ventilation for 50 years before closure

The key engineered barriers are the waste package and common drip shield without backfill. EDA IIIa uses the waste package with 2 cm of Alloy-22 over 5 cm of stainless steel. EDA IIIb uses an enhanced performance waste package that includes an outer layer of highly corrosion-resistant Alloy-22 over Ti-7 that are shrink-fitted together and an inner layer of stainless steel. The inner layer is slip fit (the gap between the inner and outer layers is not more than 4 mm) and provides structural stability to the waste package.

Principal Results of Evaluation—Results of evaluation indicated that for EDA III:

- Both EDAs IIIa and IIIb have a calculated peak 10,000-year radiation dose rate of 0.017 mrem/yr, an insignificant fraction of the screening level of 25 mrem/yr. The screening dose rate level is not reached until about 300,000 years, well after the screening period of 10,000 years. The calculated peak dose rate is 215 mrem/yr at 720,000 years for EDA IIIa, and 100 mrem/yr at 520,000 years for EDA IIIb. The 10,000-year dose rate is entirely due to an assumed juvenile failure of one waste package at 1,000 years.
- The Ti-7 layer in the waste package in EDA IIIb increases defense-in-depth performance.
- High temperatures throughout the potential repository adversely affect the licensing factors (e.g., by creating the possibility that water would “pool” above this region and perhaps flow back into some drifts and onto the hot waste packages).
- Shorter total drift length and avoidance of blending reduce complexities in construction and operation compared with the cooler designs.
- About 740 acres would be required, using only part of the upper emplacement level of the characterized area.
- EDA III performs best in terms of flexibility.

EDA IV—Shielded Waste Package Design

This design seeks to enhance accessibility to the drifts for off-normal events by increasing the degree of radiation shielding provided by the waste package. It uses a very thick waste package wall to limit the dose rate from gamma radiation at the surface of the waste package to 200 mrem/hr. The only additional requirements for access would be blast cooling to reduce the temperature in the drifts and the placement of relatively light portable neutron shielding made of 5-cm thick borated polyethylene. The design eliminates the need for the portable 20-cm steel gamma radiation shielding and the shielding at the emplacement drift entrances required in all of the other EDAs. This EDA was designed to maintain uniform and acceptably high postclosure temperatures for the drift wall and waste packages. The goals are to dry out the pillars between the drifts and keep the drifts dry for as long as possible. It was expected that in this environment, the lifetime of the thick, single-layer waste package would be greater than 10,000 years.

Key Design Features—Thermal management features include:

- Wide drift spacing (56 m, nearly double the Viability Assessment design spacing) to limit the effects of the heat from each drift on its neighbors, which enables the cladding and drift wall limits to be met
- Close waste package spacing (line loading)

- Active ventilation for 50 years before closure
- Backfill to maintain hot, dry conditions around the drip shield and waste package

The key engineered barriers are the shielded waste package and drip shield, with backfill covering the drip shield. The waste package is a single 30-cm layer of carbon steel, which allows corrosion at a predictable rate. The backfill provides added protection against rockfall and helps delay the time when corrosion begins by keeping the drip shield and waste package hot and dry for an extended period.

Principal Results of Evaluation—Results of evaluation indicated that for EDA IV:

- The peak 10,000-year radiation dose was 0.00014 mrem/yr, an insignificant fraction of the screening level of 25 mrem/yr. However, the faster corrosion of the carbon steel package after the thermal period produces the earliest arrival at 25 mrem/yr (100,000 years, well after the screening period of 10,000 years) and the highest long-term peak dose rate (1,200 mrem/yr at 320,000 years). The 10,000-year dose rate is entirely due to an assumed juvenile failure of one waste package at 1,000 years.
- High temperatures throughout the potential repository adversely affect licensing factors (e.g., by creating the possibility that water would “pool” above this region and perhaps flow back into some drifts and onto the hot waste packages).
- Shorter total drift length and the avoidance of blending reduce complexities in construction and operation compared with the cooler designs.
- Manufacturing and closing the very thick waste packages add complexities.
- About 740 acres are required, using only part of the upper emplacement level of the characterized area.

EDA V—Very High Thermal Loading Design

This alternative creates an environment in which water is driven away from the engineered barrier system and the waste package for as long as practicable. Other goals are to avoid extended periods of warm, moist conditions conducive to corrosion and to completely dry out the pillars between the emplacement drifts. This design would allow a maximum drift wall temperature of 225°C, slightly higher than the 200°C limit assumed in the other EDAs. The rationale for allowing a higher drift wall temperature was to maximize the potential benefit of mountain-scale heating while minimizing the constraints on local temperatures. For the drift wall limit, the increase in rock thermal expansion coefficient becomes steeper at about 225°C. The analyses showed that the relaxed drift wall limit was not required, and that the Viability Assessment limit of 200°C could have been used.

Key Design Features—Thermal management features include:

- Relatively close drift spacing (32 m) to ensure that the pillars are completely dried out
- Close waste package spacing (line loading)
- Blending to reduce the variation in waste package heat output
- Active ventilation for 50 years before closure

The key engineered barriers are the waste package (2 cm of Alloy-22 over 5 cm of stainless steel) and common drip shield without backfill.

Principal Results of Evaluation—Results of evaluation indicated that for EDA V:

- Peak 10,000-year radiation dose rate is 0.02 mrem/yr, an insignificant fraction of the screening level of 25 mrem/yr. The screening dose rate level is not reached until after 300,000 years, well after the screening period of 10,000 years. The long-term peak dose rate of 200 mrem/yr occurs at 720,000 years. The 10,000-year dose rate is entirely due to an assumed juvenile failure of one waste package at 1,000 years.
- Design met temperature constraints with large margin.
- Extended period of corrosive conditions was not avoided, leading to failure of about 4 percent of the waste packages between 10,000 and 100,000 years (further optimization could have produced longer dry out while not exceeding the drift wall and cladding temperature constraints; this may have reduced the waste package localized corrosion failures).
- High temperatures over large areas introduce the greatest potential uncertainties in the performance of the natural barrier system, adversely affecting licensing.
- Shortest total drift length results in less construction.
- Only 420 acres are required, allowing the potential repository to be located in a portion of the lower emplacement level that is expected to have about half the percolation flux of the upper emplacement level.

General Observations From the Evaluation of EDAs

General observations include:

- All of the EDAs performed very well relative to the 25 mrem/yr screening criterion. All had calculated peak dose rates in the expected 10,000-year regulatory period of at least a factor of 1,200 lower than the 25 mrem/yr screening criterion, and none reached that level before approximately 100,000 years.
- A Ti-7 drip shield appears to be able to protect the waste packages from dripping water for thousands of years, allowing the temperature of the waste packages to fall below the level of localized corrosion vulnerability before they could be contacted by dripping water.

- The waste package design used in most EDAs (corrosion-resistant Alloy-22 over stainless steel) appears capable of achieving a minimum life of 100,000 years, when protected by drip shields, in the anticipated environment in the potential repository at Yucca Mountain.
- Lower temperatures reduce uncertainties in localized corrosion, rock alteration, and coupled processes in the natural system, thereby improving factors affecting licensability.
- Higher temperatures allow use of larger capacity waste packages and shorter total emplacement drift length that must be excavated. This reduces the probability of industrial accidents during construction and operation, and reduces net costs.
- Higher areal mass loading provides more flexibility with respect to the location of the potential repository within the characterized area, the ability to adapt to the discovery of regions that should be avoided, and the ability to increase capacity (should an increase be authorized).

O.2.2.3 Comparative Evaluation of the Enhanced Design Alternatives

After completing the individual EDA analyses, the LADS team ranked the EDAs according to each evaluation criterion by comparing them directly against each other. The ranking, which was based on qualitative judgment rather than on quantitative scoring, took into account all of the information available to the team at the time. This information included the evaluations of the EDAs considered separately, the insights gained over the course of those evaluations, additional analyses that became available after the evaluations were completed, and discussions of those evaluations during a two-day EDA evaluation workshop held immediately before the ranking took place. The results of this ranking process are shown in Table O-4.

Table O-4. Enhanced Design Alternative Ranking Against Evaluation Criteria

Enhanced Design Alternative Ranking for Performance Demonstrability	Enhanced Design Alternative Ranking for Flexibility	Enhanced Design Alternative Ranking for Construction, Operations, Maintenance	Enhanced Design Alternative Ranking for Cost
I	IIIa, IIIb	V	II, IIIa, IIIb, IV, V
II	V	IIIa	I
IIIb	II	II	
IIIa	IV	IIIb	
V	I	I	
IV		IV	

The team ranked the EDAs into two groups with respect to cost: EDAs II through V, and EDA I. The estimated costs of EDAs II through V (\$19.9 to \$21.1 billion repository life cycle costs and \$10.7 to \$11.4 billion net present value) are grouped so closely together that distinctions in rank would not be warranted. However, EDA I has a distinctly higher cost (\$25 billion repository life

cycle cost and \$13.4 billion net present value) because it requires a substantially larger number of waste packages and greater length of drift construction than any of the other EDAs.

O.3 DESIGN RECOMMENDATION

Using the evaluations of the EDAs and their rankings within each of the criteria as a basis, the LADS core team and M&O management group identified the design to be recommended to DOE. First, the bases for these rankings, including the technical evaluations that led to them, were reviewed and discussed in a meeting with the LADS core team and M&O management. The participants then considered which design—and its associated thermal goals—most consistently ranked highly against the four criteria. No attempt was made to explicitly weight or otherwise specify the relative value of individual criteria. Instead, the participants considered the consistency of rankings across multiple criteria; an EDA that ranked well in all of the criteria was considered to be preferable to an EDA ranking highly on one or two criteria but poorly on others.

Table 0-5 summarizes the key issues resulting from the analysis of the EDAs that were considered in arriving at a design recommendation. All of the EDAs displayed excellent postclosure performance with large margins compared to the screening criterion of 25 mrem/yr in the first 10,000 years. Key issues for discriminating among the designs related to the uncertainties in postclosure performance and the ability to demonstrate that performance. Of particular importance were those uncertainties that result from coupled thermal-hydrologic processes in the rock surrounding the drifts and thermally driven crevice corrosion of the Alloy-22 waste package material. EDAs I and II were judged to provide significantly fewer uncertainties in these areas relative to the other EDAs due to their lower temperatures, and EDA I was particularly advantageous in keeping temperatures low enough to mitigate uncertainties associated with natural system coupled processes and localized corrosion on the drip shields and waste packages.

In the area of construction, operations, and maintenance, all of the EDAs except EDA I had comparable operational issues associated with the excavation of drifts and emplacement of waste packages, since these EDAs all used essentially the same number of waste packages and length of emplacement drifts. EDA I was additionally burdened in this area, which affects the likelihood of industrial accidents, because compared to the other EDAs, it required about 60 percent more waste packages and more than twice the emplacement drift length. These differences compared with the other EDAs resulted from the two additional thermal management measures that were required to achieve the low temperature goals of EDA I: use of a larger number of substantially smaller waste packages (having slightly less than 60 percent of the capacity of those used in the other EDAs), and increased spacing between the waste packages (from the 10-cm line load spacing of the other EDAs to a 3-m point load spacing).

In terms of flexibility, compared with the other EDAs, EDA I was capable of handling less additional capacity within the area that has already been characterized. EDA II was judged to be particularly flexible in its ability to change to a lower or higher temperature design, if required. A transition to the temperature goals of EDA I could be accomplished through extension of the ventilation period in EDA II, without repackaging the waste or separating the existing waste

Table O-5. Principal Results of Analysis of Enhanced Design Alternatives

Performance Categories		EDA I	EDA II	EDAs IIIa/IIIb	EDA IV	EDA V
Performance Factors	Margin	2,500	3,550	1,500	180,000	1,250
	Time to 25 mrem	290,000 years	310,000 years	290,000/ 310,000 years	100,000 years	300,000 years
	Peak Annual Dose	85 mrem	85 mrem	215/100 mrem	1,200 mrem	200 mrem
Performance Demonstrability Factors	Rock Temperatures	Always below 96°C	Rock for several meters around drifts exceeds boiling point of water for several hundred years	Above-boiling conditions extend across most of repository	Above-boiling conditions extend across most of repository	Above-boiling conditions extend across essentially all of repository
	Waste Package Corrosion	Never enters aggressive corrosion range	Never enters aggressive corrosion range	Some waste packages in aggressive corrosion range for thousands of years	Humid air corrosion of waste packages begins as early as 100 years	Some waste packages in aggressive corrosion range for over 10,000 years
Construction, Operations, and Maintenance Factors	Number of Waste Packages	15,903	10,039	10,213	10,213	10,039
	Length of Emplacement Drifts ¹	132 km	54 km	55 km	60 km	54 km
	Key Construction, Operations, and Maintenance Issues	Operational impacts of more packages and longer drifts; blending	Blending; emplacement of backfill	Fabrication of dual corrosion-resistant material package in IIIb	Fabrication, welding, and handling thick waste packages; emplacement of backfill	Blending
Flexibility Factors	Emplacement area for 70,000 MTHM	1,400 acres	1,050 acres	740 acres	740 acres	420 acres
	Ability to Change to Lower Temperature	N/A	Requires longer ventilation	Requires changes in drift spacing	High temperature is integral to waste package performance	Requires changes in drift spacing
	Ability to Change to Higher Temperature	Requires development of larger packages and coupled models for performance assessment	Requires development of coupled models for performance assessment	N/A	N/A	N/A

Table O-5. Principal Results of Analysis of Enhanced Design Alternatives (Continued)

Performance Categories		EDA I	EDA II	EDAs IIIa/IIIb	EDA IV	EDA V
Cost	Repository Life Cycle Cost	\$25.1 billion	\$20.6 billion	\$20.1 billion/ \$21.3 billion	\$21.7 billion	\$20.0 billion
	Net Present Value	\$13.4 billion	\$11.0 billion	\$10.7 billion/ \$11.4 billion	\$11.3 billion	\$10.8 billion

¹ Emplacement length does not include perimeter drifts, maintenance drifts, performance confirmation drifts, or contingency area. Lengths were calculated as follows:

- (a) The EDA II length (from CRWMS M&O 1999w) was divided by its number of waste packages to obtain the average drift length used for each package and associated gap.
- (b) This length was adjusted for the other EDAs: (I) 2.9 m were added to account for the gap increase from 10 cm to 3 m; (III and V) no change; (IV) 46 cm were added to account for the two thicker lids, 30 cm rather than 7 cm.
- (c) The adjusted average lengths were multiplied by the number of waste packages for each EDA.

packages. In contract, physical changes to the repository layout would be required in the EDAs having more extensive thermal effects. All of the EDAs were comparable in terms of estimated total repository life cycle cost and net present value cost except EDA I, which was about 20 to 25 percent higher than the other four EDAs, primarily because of the larger number of waste packages and additional emplacement drift length.

Taking all of the considerations into account, the M&O recommended that EDA II be taken forward as the candidate conceptual design for the possible Site Recommendation and License Application. The recommended design provides a good balance of the ability of lower temperature designs to reduce uncertainties about postclosure performance and the preclosure advantages that designs with greater thermal effects can offer in the areas of construction and operations, flexibility, and cost.

O.3.1 Key Elements of the Recommended Design

The basic thermal design goals of the recommended design are to keep the centers of the pillars between the loaded emplacement drifts below the boiling point of water and keep the spent nuclear fuel cladding below 350°C. A set of design parameters that meet these goals are presented in Table O-6.

Table O-6. Comparison of Enhanced Design Alternative II and Viability Assessment Design

Design Characteristics	EDA II	Viability Assessment Design
Areal Mass Loading	60 MTHM/acre	85 MTHM/acre
Drift Spacing	81 m	28 m
Drift Diameter	5.5 m	5.5 m
Waste Package Spacing	Line loading: 10 cm	Point loading: Spacing varies (several meters)
Total Length of Emplacement Drifts	54 km	107 km
Ground Support	Steel	Concrete lining
Invert	Steel with sand or gravel ballast	Concrete
Number of Waste Packages	10,039	10,500
Waste Package Materials	2-cm Alloy-22 over 5-cm stainless steel 316L	10-cm carbon steel over 2-cm Alloy-22
Maximum Waste Package Capacity	21 PWR assemblies	21 PWR assemblies
Peak Waste Package Power (blending)	20% above average PWR waste package power	95% above average PWR waste package power
Drip Shield	2-cm Ti-7	None
Backfill	Yes	None
Preclosure Period	50 years	50 years
Preclosure Ventilation Rate	2 to 10 m ³ /s	0.1 m ³ /s

Further development is required to bring this conceptual design to the level of detail required for the possible Site Recommendation and License Application. The design goals would remain fixed while other elements of the design would be refined to balance safety, cost, flexibility, and constructability.

O.3.2 Major Characteristics of the Recommended Design

Performance—Projections of performance using central estimates and TSPA-Viability Assessment models indicate that the recommended design, if implemented at Yucca Mountain, would perform extremely well with respect to a screening criterion of 25 mrem/yr to an average member of a critical group living 20 km from the potential repository during the first 10,000 years. A calculated dose rate of 25 mrem/yr would not be reached for more than 300,000 years, and the dose rate at any time would be less than 100 mrem/yr. The calculated time of the first corrosion failure of a waste package is about 100,000 years.

Reduced Uncertainty—The recommended design offers a number of advantages for the licensing safety case compared with designs with more extensive thermal effects (including the Viability Assessment design). First, it reduces or avoids uncertainties associated with the thermal pulse when large quantities of water could possibly pool above the repository and then subsequently flow into the drifts where it could corrode the hot drip shields or waste packages. It does this by keeping larger areas of very wide pillars cool enough to allow water to move around the drifts and drain through the pillars. Second, while the design would heat the rock above boiling for several meters around the emplacement drift, this would occur for a shorter time—only several hundred years—than expected with a design having more extensive thermal effects. By raising only a small quantity of the rock mass above the boiling point of water for a relatively brief time period, the potential for long-term hydrological and geochemical alteration of the host rock is reduced. This is expected to reduce the uncertainties associated with modeling the performance of the host rock. Third, the wide drift spacing reduces the analytical complexities resulting from temperature interactions among closely spaced drifts, simplifying the analysis of repository performance and allowing the segregation of DOE spent nuclear fuel and high-level radioactive waste packages in separate drifts without affecting throughput. Finally, the design limits the time that the waste package outer barrier (Alloy-22) would be vulnerable to aggressive localized corrosion from contact with hot water to a period that is substantially less than the expected life of the drip shield. As a result, the Alloy-22 waste package outer barrier material is subject only to very slow general aqueous corrosion from seepage water and/or condensation.

Construction/Operations—The recommended design achieves many of the operational benefits of designs having more extensive thermal effects in terms of the ability to use larger waste packages and reduce the length of emplacement drifts that must be excavated compared with the lowest temperature design, EDA I. (EDA I required 60 percent more waste packages, and more than twice the emplacement drifting, with a proportionate increase in the probability of industrial accidents during construction and operation.)

The recommended design also provides operational flexibility by allowing the cooler defense high-level radioactive waste to be placed into drifts separate from the hotter commercial spent nuclear fuel if desired. The combination of blending and the wide drift spacing reduces the possibility that warmer waste packages in one drift might cause water to move toward the cooler

drifts. In effect, a drift filled with the cooler waste packages would see conditions similar to the long-term ambient conditions. The potential for separate emplacement of hotter and cooler waste packages avoids the need for a careful staging and sequencing of the emplacement of DOE and commercial waste packages assumed in the Viability Assessment design and the higher areal mass loading EDAs.

Technical and Programmatic Flexibility—The recommended design provides very good programmatic flexibility to adapt the program to changes, while allowing focused progress toward a design that can be licensed with a high degree of confidence if the site proves suitable. Possible factors leading to such changes include new scientific and engineering knowledge or a shift in national priorities that may dictate a change in repository capacity or time of repository closure. The recommended design provides a path forward that can accommodate future revision of major program goals or repository design attributes.

The recommended design offers this flexibility in several ways. For example, transition to either higher or lower temperature goals is possible should these be deemed appropriate later. Little additional technology development would be required, since the recommended design and EDAs I and V use similar blending facilities and a waste package design with identical shell materials and thicknesses. No additional site characterization would be needed for transition to lower temperature goals by extending the preclosure ventilation period. Some additional performance assessment work would be required to deal with the greater extent of thermal perturbation associated with higher temperature goals. In addition, the long preclosure ventilation period allows time to gather additional data that might support modifications to the repository before closure. For example, provision of defense in depth through a drip shield added only at closure allows for optimization based on further data and analysis during the preclosure period. Finally, although the design requires 40 percent more area than the Viability Assessment design, it could accommodate 105,000 metric tons of waste, if such an increase in capacity is authorized, within an area that has already been characterized.

Cost—The estimated cost of the recommended design is similar to the cost of the higher areal mass loading designs and is 25 percent lower than the very low temperature design of EDA I. Although the estimated cost is about 20 percent higher than the Viability Assessment design, most of these costs are associated with fabrication and emplacement of the drip shield and installation of backfill. These costs would not be incurred until closure of the repository, because technical and fiscal considerations favor emplacement as late as possible. The net present value cost of the recommended design, which takes into account the long delay in the expenditures on the drip shields and backfill, is only about 8 percent higher than the net present value cost of the Viability Assessment design.

1. INTRODUCTION

In 1998, the U.S. Department of Energy (DOE) directed the Management and Operating Contractor (M&O) to conduct a formal study of alternative design concepts for a potential geologic repository for spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nevada (see Appendix A, License Application Design Selection Project Direction and Guidance, M&O Contractor Level 3 Milestone). The study, called the License Application Design Selection (LADS) project, was initiated in early July 1998, and resulted in the development and submission of the report in April 1999. The major tasks of the study were to:

- Identify design alternatives (DAs) to the overall repository concept
- Specify features that might improve the performance of the different DAs
- Evaluate those alternatives and features individually by using available information and resources
- Define enhanced design alternatives (EDAs) (i.e., various combinations of alternatives and features)
- Evaluate the final set of EDAs according to evaluation criteria, such as performance demonstrability, cost/schedule, construction/operations/maintenance, and flexibility
- Recommend a conceptual design plus option(s) for enhancement
- Recommend trade studies and data acquisition activities needed for the conceptual design to proceed to the possible Site Recommendation and License Application

To guide and facilitate the study, the LADS project made use of recognized decision analysis theories and processes, as described in Section 3. The purpose of the study was to help DOE select the geologic repository design concept that would be further developed to support the Site Recommendation and License Application milestones.

The goal of the LADS project was to consider a diverse range of designs and arrive at a recommended design concept. DOE will then review the recommendation and select a design concept for further consideration. Note that the LADS recommendation is for a conceptual design; preliminary design and final design activities will occur following the LADS project to appropriate levels of detail for the Site Recommendation and License Application milestones. As such, the design features (DFs) and DAs considered in the LADS project are conceptual in nature. In this way, a wide variety of design concepts could be considered. Different amounts and quality of data exist regarding different design concepts, but by keeping the evaluations at a conceptual-design level, the LADS evaluation team was able to consider a diverse range of possible design options.

The LADS process consisted of two phases, as discussed in Section 3.2. Phase I began with the identification of DAs and DFs that were subjected to engineering analysis and evaluation. A set of evaluation criteria was established to evaluate each DA and DF, consisting of both quantitative measures (e.g., postclosure performance) and more qualitative measures

(e.g., operability). The Phase I activities concluded with the identification of a candidate set of EDAs that represented complete design concepts. Phase II began with the refinement of the candidate set of EDAs down to a final set of five EDAs that were subjected to more detailed evaluation. Phase II evaluation criteria were identified that included aspects related to a range of design attributes (e.g., performance demonstrability). The conclusion of Phase II was marked by the evaluation of each EDA against each criterion, then comparative evaluations of all EDAs against these criteria and, finally, the recommendation of a conceptual design and options to DOE.

The LADS project began by establishing a set of DAs and a set of DFs. Examples of DAs for a geologic repository might include postclosure ventilation designs and low thermal-load designs. Both serve the same fundamental purpose—disposal of spent nuclear fuel and high-level radioactive waste. In general, the DAs represent fundamentally different conceptual designs for the potential repository and, potentially, could stand alone as the repository design concept for the possible License Application; these various DAs are listed in Section 4.1. DFs, such as drip shields and backfill, are more limited features that could be added to a particular DA to enhance its performance; the available and relevant DFs are also listed in Section 4.1. The DAs were evaluated relative to their basic attributes, such as cost, performance, and flexibility. The DFs were evaluated relative to their own basic attributes and then relative to their ability to enhance the attributes of the design in the Viability Assessment (DOE 1998b).

DFs were combined with DAs to create EDAs. Several combinations were created and evaluated, as described in Section 5. The evaluation consisted of generating, compiling, and documenting available information (cost, performance, etc.) for each of the EDAs.

The final step was to perform comparative evaluations among the EDAs using the Phase II criteria. It was first determined that all of the EDAs that made it to this last step were, in fact, feasible. That is, there is a reasonable probability that they all can be constructed, licensed, and operated within the appropriate programmatic and regulatory constraints. Then, the Phase II criteria were used to conduct comparative evaluations between the various EDAs. The Phase II criteria are discussed in Section 5.2, while the comparative evaluations of the EDAs are presented in Section 6.2. Conclusions and recommendations were then drawn from the results of this final step and are presented in Section 7.

The LADS process benefited from the review and comment from multiple review groups, including the Repository Consulting Board, the Design Alternatives Review Panel, and the Nuclear Waste Technical Review Board. High-level M&O and DOE management oversight and direction were provided by the License Application Design Integration Group. This direction is summarized in Appendix B, License Application Design Integration Group Guidance and Direction (Brocoum 1999).

1.1 OBJECTIVE

This report documents the activities involved in describing and evaluating a wide range of conceptual DAs and DFs for a potential repository for disposal of the nation's spent nuclear fuel and high-level radioactive waste at Yucca Mountain, Nevada. It also describes the results of the evaluation and selection activities, and the conclusions and recommendations drawn from these activities.

The specific objectives of the LADS project were to create and document essential information about, and reasonable recommendations for, conceptual repository designs. These conceptual repository designs must address the following objectives:

- Provide postclosure performance that satisfies the appropriate regulatory standards and guidelines for waste isolation and containment, with sufficient margin to account for uncertainties
- Provide preclosure performance that satisfies regulatory standards for radiological protection of workers and members of the public, while also complying with all other relevant safety and environmental regulations (e.g., Occupational Safety and Health Administration requirements)
- Provide confidence in, and flexibility of, the design
- Provide effective security and safeguards for all nuclear materials
- Provide a low level of licensing risk
- Provide reasonable cost estimates without compromising other criteria

This report will further define and document these objectives as they were developed into evaluation criteria. The first set of evaluation criteria was used to structure and guide the development and analyses of the DAs and DFs in Phase I. A second set of evaluation criteria was created to guide the development and evaluation of EDAs in Phase II; this set consolidated the initial set and added system level criteria such as defense in depth.

This report directly supports the successful completion of the DOE Level 2 Milestone (Select Initial Site Recommendation/License Application Design and Options [M2MQ]). In addition, this report and its supporting documentation address the 10 CFR 60.21 requirement for comparative evaluation of alternatives to major features of the design that are important to waste isolation and containment performance.

1.2 SCOPE

The scope of this report is limited to consideration of the disposal of commercial and DOE spent nuclear fuel and of high-level radioactive waste in an underground repository to be located, potentially, at Yucca Mountain, Nevada. For the vast majority of the radionuclides that could be emplaced in the repository, the Yucca Mountain site alone (the natural barrier system) appears to be completely capable of containing them and preventing any migration into the groundwater system. That leaves a small fraction of the radionuclides that appear to be mobile and, under some circumstances, could migrate away from the repository if they are exposed to liquid water. This concern can be mitigated if an engineered barrier system is able to limit the exposure of these radionuclides to water. Therefore, waste isolation relies on the low flux of water through the repository at this site and engineered barriers to divert even this small amount of water away from the waste for a very long time.

The LADS activities included the identification, development, and evaluation of various engineered barrier concepts derived from a wide range of DAs and DFs.

Candidate DAs and DFs are focused on postclosure performance, but the report also addresses the other characteristics associated with the objectives of the LADS activities given above. Characteristics and features excluded from the LADS activities include waste transportation, waste-stream characteristics, and use of unproven technology.

A number of issues, concerns, and studies related to the Office of Civilian Radioactive Waste Management program were evaluated for their potential influence on the LADS project. Where appropriate, these topics were integrated into the scope of the LADS project. In other areas, the efforts were kept separate, but coordinated to ensure consistency. These topics are identified and briefly discussed in Appendix C, Other Considerations.

1.3 BACKGROUND

1.3.1 U.S. Nuclear Regulatory Commission Regulations

As documented in 10 CFR 60, regulations for submitting a License Application require that the "Content of Application" section include a list of necessary components. Specifically, 10 CFR 60.21.c.1.ii.D requires that the Safety Analysis Report must include "a comparative evaluation of alternatives to the major DFs that are important to waste isolation, with particular attention to the alternatives that would provide longer radionuclide containment and isolation" (10 CFR 60).

1.3.2 U.S. Department of Energy Level 2 Milestone

In response to the U.S. Nuclear Regulatory Commission requirement, DOE established a milestone that documents the identification of the initial Site Recommendation and License Application design concept and attendant options. The complete description of this milestone is provided in Appendix A.

1.3.3 Management and Operating Contractor Level 3 Milestone

The Level 3 Milestone for the LADS report was based on the above requirements for the Level 2 Milestone. DOE provided specific guidance for the conduct of the LADS study. The complete text of this guidance is provided in Appendix A. As part of the multi-year planning baseline, the milestone description and evaluation criteria provide further guidance in the preparation of this report. The text of this guidance is also provided in Appendix A.

1.3.4 License Application Design Selection Team

On July 7, 1998, the M&O Assistant General Manager of the Monitored Geologic Repository created the LADS project and assigned a manager to run it. The project manager assembled a LADS team consisting of senior members from most of the M&O operations areas. The organization of the LADS team is illustrated in Figure 1-1. The core team consisted of scientists and engineers who reported directly to the project manager and were held accountable for the successful completion of the LADS project. The expanded team included scientists and

engineers who were responsible for maintaining an effective interface between the LADS project and the supporting organizations within the M&O. The DA/DF/EDA leads are engineers who were assigned the responsibility of developing, evaluating, and reporting on each of the DAs, DFs, and EDAs. The criterion leads are scientists and engineers who were assigned to each EDA criterion to ensure consistent and appropriate application of the EDA evaluation criteria. Members of the expanded team, DA/DF/EDA leads, and criteria leads were temporarily assigned to support the LADS project, but did not report directly to the LADS project manager. The decision analysis consultants were responsible for developing processes to arrive at a design recommendation and for facilitating interaction within the LADS team. The LADS team was tasked with implementing the LADS activities in accordance with the LADS plan (CRWMS M&O 1998b). These activities led to the documentation within this report of EDA concepts needed to support the selection of a conceptual design to start the Site Recommendation/License Application design activity. This report was prepared in accordance with the directions of the LADS technical document preparation plan (CRWMS M&O 1999a).

Figure 1-1. License Application Design Selection Team Organization

1.3.5 Environmental Considerations

The designs developed during the LADS activity were reviewed to ensure that the thermal load-implementing alternatives of the anticipated draft environmental impact statement bounded the potential impacts of the LADS designs under construction. Alternatives in the anticipated draft environmental impact statement having to do with transportation to the repository, and the “no action” alternative, were excluded from the scope of the LADS project. Environmental considerations were addressed and documented for each of the DAs, DFs, and EDAs that were evaluated.

1.4 QUALITY ASSURANCE

The quality assurance program applied to the development of this report. The M&O LADS project manager evaluated the technical document development activity in accordance with QAP-2-0. The QAP-2-0 activity evaluation (CRWMS M&O 1998e) determined that the preparation and review of this document is subject to *Quality Assurance Requirements and Description* (DOE 1998a) requirements. The activity evaluation also determined that the classification of items in accordance with QAP-2-3 is not required. Any such classification will be performed on the selected design at the appropriate point in the design process.

Since unqualified inputs were used in the development of this report, they should be considered TBV (to be verified). This document will not directly support any construction, fabrication, or procurement activity and, therefore, the inputs and resulting recommendation are not required to be procedurally controlled as TBV and tracked in accordance with NLP-3-15. However, use of any data from this report for input into documents supporting procurement, fabrication, or construction is required to be controlled as TBV in accordance with appropriate procedures.

2. REQUIREMENTS AND ASSUMPTIONS

Many of the assumptions used in this report would be design or programmatic requirements for a detailed repository design. Since the goal of this report is conceptual in nature, these are not listed separately as requirements. Additional assumptions used in evaluating individual designs are included in those analyses. The selection and recommendation of the repository design used the following assumptions, which are compatible with, but not inclusive of, all those assumptions used to evaluate individual design features, design alternatives, and enhanced design alternatives (EDAs).

For the purpose of creating candidate EDAs, all statutory and regulatory requirements governing the potential repository design and the concept of operations were assumed to be bounding and limiting so that no repository design proposed, evaluated, or recommended in this report shall exceed or violate the limitations of such requirements (DOE 1998b, Vol. 2, Section 3.1). The EDAs in Section 5 reflect this. These requirements are included in the following documents:

- Nuclear Waste Policy Act, as amended
- 10 CFR 60¹
- 10 CFR 20
- 10 CFR 73
- EIA 1996
- YMP 1998

During the first 10,000 years after the closure of the repository, it was assumed the postclosure performance requirement for the expected annual dose to an average individual of a critical group living 20 km from the repository will not exceed 25 mrem from all pathways and all radionuclides. This assumption is consistent with the U.S. Nuclear Regulatory Commission's proposed site-specific regulation (see 64 FR 8640) for Yucca Mountain, until such time as the U.S. Environmental Protection Agency issues a Yucca Mountain, Nevada, specific standard as directed by the U.S. Congress. This assumption was made for all postclosure performance evaluations in this report.

Commercial spent nuclear fuel received at the potential repository from pressurized-water reactors was assumed to be, on average, 25.9 years out-of-reactor, with a 3.69 weight percent initial enrichment and a burn-up value of 39.56 gigawatt days per metric ton of heavy metal (MTHM). Commercial spent nuclear fuel received at the potential repository from boiling-water reactors was assumed to be, on average, 27.2 years out-of-reactor with a 3.00 weight percent initial enrichment and a burn-up value of 32.24 gigawatt days per MTHM (CRWMS M&O 1998a, Key 004). These values were taken directly from the cited reference and were averaged from a wide range of values of both time out-of-reactor and enrichment.

For the purposes of cost analysis in Section 5.3, the scenario used in the Viability Assessment (DOE 1998b) cost analysis was assumed. This assumed that the youngest fuel (at least 10 years old) arrives first from utilities with oldest-fuel-first acceptance rights. The waste stream arriving at the potential repository was assumed to be that which was described in the Viability

¹ As the License Application Design Selection project progressed, the proposed rule 10 CFR 63 was released (see 64 FR 8640). All conceptual design decisions were consistent with the proposed regulation.

Assessment (DOE 1998b, Vol. 2, Section 3.1.1, Table 3-1). Defense waste was assumed to be received and emplaced according to the schedule in the Viability Assessment, with the first material received in 2010 (DOE 1998b, Vol. 2, Section 3.1.1, Table 3-1). The quantity of waste to be received was assumed (from the Viability Assessment) to consist of 63,000 MTHM of commercial spent nuclear fuel and a total of 7,000 MTHM-equivalent of U.S. Department of Energy spent nuclear fuel and high-level radioactive waste.

The net present value costs (1998 dollars) are calculated with a 2.3 percent real annual interest rate (net of inflation) based on economic assumptions used in analyses of the adequacy of the Nuclear Waste Fund (DOE 1998c).

A glossary defining technical terms used in this report is included as Appendix D.

3. PROCESS

In addition to the engineering activities associated with developing conceptual designs, the License Application Design Selection (LADS) involved decision processes. Decision analysis consultants provided guidance in developing a decision process consistent with the conceptual design process and in facilitating interactions with the LADS team members. It is the responsibility of the Management and Operating Contractor (M&O) to provide a conceptual design to the U.S. Department of Energy (DOE) that will be used as an initial design to be further developed for the possible Site Recommendation and License Application, should the site prove suitable. The responsibility for the design recommendation was assigned to the M&O; the design selection will be made by DOE. Because the design carried forward into Site Recommendation and License Application is a joint decision responsibility, both M&O and DOE management provided their input into the decision methodology and implementation.

This section provides a description of the overall decision process used in the LADS project. Methodology descriptions in subsequent sections of the report describe the processes used to implement specific components of the overall decision process (e.g., Sections 5.1 and 6.1). In the following paragraphs, certain important implementation approaches are discussed (e.g., the use of workshops).

3.1 ATTRIBUTES OF OVERALL DECISION PROCESS

The LADS process was a conceptual design process guided by the general principles of decision making. In a typical alternatives-selection process, the alternatives are defined prior to their ranking and selection. For example, if a decision is being made that entails the selection of one alternative from among multiple alternatives, it is usually assumed that the alternatives—once identified based on a set of explicit objectives—are essentially frozen. Consider the selection of an employee to fill a position within a company. The objectives can be specified (e.g., years of experience, academic background, expertise) and, in light of these objectives, multiple candidates can be identified. The selection of a candidate, then, will entail an evaluation of each alternative candidate against the set of objectives.

In the case of the LADS process, however, the alternatives continued to evolve throughout the course of the study. The process began with a set of “building blocks” (the design features [DFs] and design alternatives [DAs]) and a set of objectives (the evaluation criteria). From this, multiple design concepts were developed—the enhanced design alternatives (EDAs)—which were consistent with the objectives. Rather than freeze the alternatives for the subsequent evaluation, the primary emphasis of the LADS project was on the creative development of alternative designs that continued to evolve throughout the course of the project as the ongoing analysis provided additional insights. A set of five refined EDAs was then evaluated against a set of evaluation criteria in order to form a basic design concept. It is expected that the recommended design will continue to evolve even after the LADS process is complete, in order to improve the design with respect to cost, performance, and other issues. The aspect of the process that allows for continual design refinement is a strength that ensures that the recommended design will successfully meet the objectives.

A principal focus of the LADS process was the development of alternative design concepts. There have been numerous previous studies focused on the evaluation and selection of one alternative from a set of alternatives using formalized decision analysis approaches.² Rather than beginning with a set of alternatives to be evaluated, the LADS project devoted considerable effort to creating a set of alternatives. The process of making a selection from among the alternatives was then accomplished by the LADS core team and M&O management, using a consensus approach.

The decision process followed in the LADS evaluation used many of the elements of the value-focused process recommended by Keeney (1992, pp. 44-51) for making a choice among multiple alternatives. It is suggested that rather than alternatives (alternative-focused approach), the objectives or values should first be identified (value-focused approach). The alternatives could then be created (Keeney 1992, p. 49, Table 2.1) in light of the objectives. This process would be more likely to lead to the identification of alternatives that are consistent with the objectives, as well as to ensure that the fundamental objectives are met in the selection of one alternative. Keeney's suggested steps (1992, p. 49, Table 2.1) for value-focused thinking for decision problems are the following:

- Recognize a decision problem.
- Specify values.
- Create alternatives.
- Evaluate alternatives.
- Select an alternative.

The LADS decision process consisted of two phases (Figure 3-1), with the first phase resulting in the alternatives to be evaluated and the second phase resulting in a design recommendation. The decision problem was to arrive at a repository design that could be carried forward into the Site Recommendation and License Application. Values were specified through an objectives hierarchy and developed to identify the fundamental objectives—the evaluation criteria—for evaluating the DAs and DFs in Phase I and the EDAs in Phase II. The sets of criteria for the two phases were tailored to the scope of each phase. Alternatives to be evaluated in Phase II were created from the Phase I process, including both the identification of objectives and evaluation of the components of designs (i.e., the DAs and DFs). Following design development and refinement, the EDAs were evaluated against the evaluation criteria and a final design was selected. This is consistent with the value-focused approach of first considering the objectives

² Decision analysis has been used at the highest policy level to structure Germany's energy policies (Keeney et al. 1987). That study resulted in eight major objectives supported by approximately 100 detailed objectives. There have been many applications of decision analysis to nuclear materials, nuclear power, and radioactive waste disposal. Judd and Weissenberger (1982) provided a decision analysis of nuclear materials safeguards, as did Keeney and Smith (1982). Both Hobbs (1980) and Kirkwood (1982) provided analyses of nuclear power generating station siting decisions. Both of these applications employed multiple evaluation measures. Kirkwood and Sarin (1985) examined borehole plugging materials and ranked alternatives by using pair-wise comparisons. This analysis is unique in that only partial information about weights for attributes is available. Merkhofer and Keeney (1987) presented a multi-attribute decision analysis for the selection of a deep geologic repository, while Keeney (1987) took a portfolio approach. Gregory and Lichtenstein (1987) reviewed the high-level siting problem. Hora (1997) discussed a methodology for selecting scientific programs for the qualification of a radioactive waste repository; it was applied to the Waste Isolation Pilot Project in New Mexico.

and values that are desired (the evaluation criteria), developing a diverse set of alternatives that have the potential to meet these objectives, and evaluating the alternatives and selecting from among them.

Decision-Making Groups—The objective of the LADS process was to arrive at a repository design that could be carried forward into the Site Recommendation and License Application, should the site prove suitable. Although the design recommendation is ultimately the responsibility of M&O management, the decisions regarding the evaluation criteria, alternative designs for evaluation, and the development of alternative design concepts were delegated to the LADS core team. For example, the core team identified the evaluation criteria for both Phases I and II and the set of five EDAs that was carried into Phase II, and evaluated and ranked the EDAs against each criterion. These decisions were made through the development of a consensus of the team, usually accomplished in a facilitated meeting environment.

To ensure that the M&O design recommendation would be highly likely to become the design selected by DOE management, close and regular interaction occurred through the License Application Design Integration Group.³ In their deliberations, the License Application Design Integration Group and the LADS core team fully considered the design concepts and evaluations made by the large group of engineers represented in the LADS project.

Evaluation Criteria Measures—The objectives identified were derived using an objectives hierarchy (Keeney 1992, pp. 65-69) that allowed high-level objectives to be distinguished from fundamental objectives. Some fundamental objectives were associated with quantitative measures, including natural scales (such as postclosure performance measured in millirems per year). However, many of the fundamental objectives that comprised the evaluation criteria were not amenable to direct measurement or quantification. For example, the flexibility of a particular design to accommodate possible future contingencies (such as changes in regulations) has no natural quantitative measure. Yet these issues were deemed to be extremely important to the decision regarding designs. In these cases, constructed scales provided a convenient and effective means of including these elements. For example, the degree of engineering acceptance was measured on a five-point scale. Keeney (1992, pp. 101-110) describes these two types of measures as natural and constructed attributes.

Consensus Decision Process—In the LADS study, the alternatives were evaluated against the criteria, and then the alternatives were ranked against each criterion using simple pair-wise comparisons. The value trade-offs among the criteria were made implicitly by the combined LADS core team and M&O management group in arriving at a selection based on consideration of the rankings of the alternatives against each of the multiple criteria. Although the decision process followed the basic steps in an alternatives-evaluation process, a formal value-modeling step in which explicit value trade-offs are made between different objectives was not included. Rather, the decision-makers chose to follow a consensus decision process, particularly regarding

³ This group included the DOE Assistant Manager and one member for Office of Licensing and Regulatory Compliance, the DOE Assistant Manager and one member for Office of Project Execution, a Management and Technical Support Organization secretary and representatives from engineering and regulatory offices, the M&O Assistant General Manager and Deputy for the Monitored Geologic Repository, the M&O Regulatory and Licensing Director, and the M&O LADS manager.

the choice of an alternative based on the evaluations against the various criteria. This consensus process was more appropriate for an ongoing design process in which the alternatives were continually being refined to arrive at a final recommended design concept.

Workshop Interactions—Many of the steps in the decision process involved interactive meetings and workshops of the LADS core team and other participants. These workshops provided an opportunity for the exchange of ideas and data, the challenge and defense of interpretations, the development of conclusions and decisions, and real-time comments by representatives of oversight groups such as the Nuclear Waste Technical Review Board, U.S. Nuclear Regulatory Commission, and the Total System Performance Assessment (TSPA) Peer Review Panel. For example, the EDAs defined for evaluation in Phase II were developed in a 10-day workshop. Workshop participants were divided into teams assigned to focus on one of three broad alternative design concepts. Multiple interactions between the teams and their peers in the general sessions of the workshop provided a peer review of candidate design concepts. This interactive process encouraged the creativity needed for conceptual design development.

3.2 PRINCIPAL TASKS IN THE PROCESS

The decision process for the LADS project consisted of the following tasks shown in Figure 3-1:

- Phase I
 - Describe DAs and DFs
 - Develop DA/DF evaluation criteria
 - Evaluate DAs and DFs
 - Develop EDAs
- Phase II
 - Develop EDA evaluation criteria
 - Evaluate and rank the EDAs
 - Recommend design

Describe DAs and DFs—The DAs and DFs were identified based on previous work, as well as a consideration of views by other groups (see Section 4.1).

Develop DA/DF Evaluation Criteria—The Phase I assessment focused on evaluating the DAs and DFs, with the purpose of identifying those design concepts and features that would have potential merit as components of a conceptual design. An objectives hierarchy was developed by the core team to express the high-level and fundamental objectives in this evaluation (Figure 3-2). The fundamental objectives identified were composed of multiple subelements and measures termed “evaluation criteria” (see Section 4.2 and Figure 3-2). For example, as discussed in Section 4.2, several elements were identified that define the criterion termed “engineering acceptance.” To assist the design engineers responsible for the evaluations of the DAs and DFs, these elements were expressed as a series of questions. Both quantitative measures (natural scales) and qualitative measures (constructed scales) were included in the evaluation criteria. For example, postclosure safety was characterized using quantitative measures calculated from the TSPA. The TSPA model used for the Viability Assessment was

adapted, to the extent possible, to perform this analysis. In order to evaluate a large number of DAs and DFs in a short time, the performance assessment organization calculated a central estimate of performance (using a single value for most of the variables in the TSPA model), instead of calculating a range of results reflecting the uncertainties. Improved performance assessment models, based on updated scientific information, will be used in future development of the design.

Likewise, costs were measured quantitatively in dollar units (repository life cycle costs in 1998 dollars). Conversely, several criteria were measured on constructed scales (e.g., 1 to 5). Each unit of the scale was defined to allow consistent application of the criteria to the various DAs and DFs. For those criteria composed of multiple subelements, the design engineers scored each of the subelements separately and provided a total score for the criterion based on a simple average of the subelement scores.

In most cases, the constructed scales were defined relative to the performance of the Viability Assessment (DOE 1998b) design, which represented the midpoint (i.e., a 3 on a five-point scale). These constructed scales were used only to provide a degree of standardization in the evaluations of the various DAs and DFs by the lead design engineers, as discussed below. The scores provided a convenient summary indicator of the way in which the DAs and DFs were expected to change the performance of the Viability Assessment design when considered as “one-off” variations to that design. The scales were not designed to allow the scores for different criteria to be combined meaningfully in a quantitative decision methodology, and no such combination was performed in this study. Because the evaluation criteria were never used in a quantitative decision analysis, they are assumed to be essentially independent and dependencies among them (e.g., cost versus schedule) are not quantified. The technical bases for the evaluations against the various criteria, rather than the scores themselves, were the fundamental factors considered by the LADS core team in developing and evaluating EDAs.

Evaluate DAs and DFs—Each of the DAs and DFs were evaluated against the evaluation criteria by a lead design engineer. The lead design engineers were required to document the technical bases for their assessments involving their own professional judgments. Thus, the professional judgments of the engineers and the bases for those judgments are traceable to the data and information available.

In addition to the evaluations of the DAs and DFs against the criteria, the confidence in each evaluation was also assessed (see Section 4.2.4). The purpose of these confidence assessments was to provide some indication of the degree of certainty in the evaluations being made. As such, the confidence assessments were surrogates for quantitative assessments of uncertainty—particularly for those criteria measured with constructed scales. Confidence was measured on a five-point constructed scale and included the basis for the confidence assessments. The documentation of the evaluations and their confidence assessments was included in the reports for the DA and DF evaluations.

Develop EDAs—The evaluation of DAs and DFs in Phase I provided information that, together with experience and engineering judgment, was used in developing the EDAs for evaluation in Phase II. The evaluation criteria were provided to the participants to guide them in creating alternatives, as suggested by Keeney (1992, p. 49, Table 2.1). The EDA development process

was also accomplished using a workshop format (see Section 5.1.2), with multiple cycles of team interactions for detailed discussions and general sessions for review and discussion. The workshop format was structured to provide a focus on the workshop decision-making body (the core team) and to encourage the exchange of ideas. Participation was encouraged from the expanded LADS team, while observers were provided opportunities to ask questions and share their perspectives. Each team that developed candidate EDAs was expected to become an advocate for its designs and to defend its selections in the general sessions. It was expected going into the workshop that there would be differences of opinion regarding the appropriateness of various design concepts. The goal was a facilitated structured debate among the workshop participants, where technical differences of opinion could be expressed. Workshop ground rules were provided and followed regarding the conduct of the participants and observers. As such, the workshops were working sessions that facilitated the development of a set of EDAs.

The workshop resulted in the identification of eight candidate EDAs. These were later reduced to five EDAs after further consideration by the core team (Section 5.1.4.2). An important consideration throughout the workshop and in the final selection of the EDAs was the need to have a diverse set of design concepts for detailed evaluation in Phase II. The range of assigned topics for the workshop teams was designed to ensure this diversity, and the selected set of five EDAs was defined to span a range of temperature goals.

Develop EDA Evaluation Criteria—The screening and evaluation criteria for evaluating the EDAs in Phase II were specified in light of the objectives shown in Figure 3-3. To some extent, the Phase II criteria represent a consolidation of the set of criteria from Phase I. The same set of objectives was identified as being important to EDAs, but they were combined into four sets of evaluation criteria termed: performance demonstrability, construction/operation/maintenance, flexibility, and cost. Two important objectives deferred in Phase I were addressed in Phase II: defense in depth and flexibility. The measures associated with these and the other evaluation criteria are discussed in Section 5.2. A criterion lead was assigned to each evaluation criterion, who was responsible for the consistent definition and application of each criterion.

Evaluate and Rank the EDAs—The evaluation of each of the five EDAs against the criteria was conducted during a week-long series of meetings attended by the lead design engineers for each EDA, the core team lead for each EDA, the criteria leads, and other core team members. The lead design engineers were provided with the evaluation criteria early in their work, and their documentation was formatted along the lines of each criterion and its subelements. The EDA evaluations against the criteria are given in the EDA reports and are summarized in Section 5.3.

A pair-wise comparison approach was used, within each criterion, to rank the EDAs. The pair-wise evaluation expresses the relative preference between a series of pairs as a function of a particular criterion. Systematic comparisons led to a unique ranking of the EDAs against each criterion. Special care was taken to ensure that the comparisons and rankings were strictly for a single criterion and not across multiple criteria. The ranking exercise was the responsibility of the core team and was conducted in a facilitated meeting environment.

Recommend Design—A consensus process was used to identify the design for recommendation to DOE (see Section 6). The process focused on recommending a single EDA, considering the rankings for each criterion. Consensus was developed during a meeting of the LADS core team

with M&O management. The process began with a review of the LADS core team rankings of the EDAs according to each of the evaluation criteria. Next, the participants looked for those designs that appeared to rank well across multiple criteria while having no criteria that ranked poorly. Finally, taking into account the results of the rankings, the more detailed evaluations, and the value of retaining flexibility to change the design well into the preclosure period, the participants selected a preferred design from among the five EDAs. The entire LADS project was then documented for submittal to DOE.

Figure 3-1. License Application Design Selection Two-Phase Process

* Deferred to Phase II

Figure 3-2. Objectives Hierarchy for Phase I Evaluation Criteria

Figure 3-3. Objectives Hierarchy for Phase II Evaluation Criteria

4. DESIGN ALTERNATIVES AND DESIGN FEATURES

In order to make the basic decisions for Phase I of the License Application Design Selection (LADS) process, as described in Section 3, information on alternative design concepts, scientific studies, tests performed or underway, and predictions of repository performance as developed through total system performance assessment was compiled into various design options called design alternatives (DAs) and design features (DFs). The DAs and DFs also included conceptual engineering and cost analysis information, and were presented as “one-off” evaluations from the design presented in the Viability Assessment (DOE 1998b). It should be noted that the DA and DF reports were based on the changes related to the Viability Assessment design and should not be expected to be consistent with enhanced design alternative (EDA) evaluations that use a suite of synergistic features.

The initial task in performing the DF and DA evaluations was to settle on the set of DAs and DFs to be developed for evaluation. Section 4.1 discusses the development of this set of DAs and DFs.

Before the selected DAs and DFs could be evaluated, a uniform set of evaluation criteria that would ultimately lead to a design selection needed to be created. Section 3 discusses the rationale and derivation of these criteria, and they are presented in detail in Section 4.2.

Sections 4.3 and 4.4 briefly describe the selected DAs and DFs. Quality-affecting reports containing more detailed information on each DF and DA are referenced in each summary discussion. A discussion of how the Viability Assessment design and the Viability Assessment design with options contributed to the EDAs can be found in Section 5.1.6.6.

It should be noted that the description of the Viability Assessment design is presented in summary form in Section 4.3.6 as DA 6. Because each DF and DA concept is evaluated in comparison to the Viability Assessment design, an understanding of the Viability Assessment design (DOE 1998b, Vol. 2) is integral to understanding how each DA and DF functions.

4.1 SELECTION OF DESIGN FEATURES AND DESIGN ALTERNATIVES FOR PHASE I

The LADS project involved the evaluation of an assortment of design concepts, referred to as DAs and DFs, prior to their combination and evaluation as EDAs. The list of DAs and DFs from which these EDAs were composed represents a diverse and varied range of repository designs. The origin and evolution of this assortment of design concepts is the subject of this section. At the start of the LADS project, the subject of DAs for the potential repository had already been addressed. The most recent study of DAs was in the Viability Assessment (DOE 1998b). The design options, DFs, and DAs in the Viability Assessment were used as a starting point for the LADS project. Those design concepts in the Viability Assessment were, in turn, drawn from previous work. The Viability Assessment documented the DA findings of the Repository Design Alternative Working Group (DOE 1998b, Vol. 2, Section 8.2.5).

The Repository Design Alternative Working Group identified a set of interdependent design concepts having attributes that work together to meet the design goals. The LADS project included these interdependent concepts as DAs. The Repository Design Alternative Working

Group also identified a number of independent design concepts which could be grouped in many combinations, including combinations with the DAs. The LADS project included these independent concepts as DFs.

The LADS project used the DAs and DFs developed by the Repository Design Alternative Working Group and documented in the Viability Assessment as an initial list for consideration. The preliminary list of DAs and DFs based on the Viability Assessment was reviewed by senior U.S. Department of Energy and Management and Operating Contractor management. Their review resulted in the addition of a DF and a DA to the list. Members of the LADS core team conducted an extensive review of the Viability Assessment list of DAs and DFs and added another DF, in addition to combining or subdividing some of the DFs for ease of analysis.

In the DA/DF list review, the LADS core team specifically included a review of the design-related concerns provided by stakeholder and oversight groups. Sources of information included Nuclear Waste Technical Review Board reports, correspondence, and personal communications; U.S. Nuclear Regulatory Commission key technical issue reports; and reports by the University of Nevada–Reno and the Nye County Nuclear Waste Repository Project Office. (See Table 4-1 for a list of the specific references that were reviewed.) Design issues raised by these groups were covered by DAs and DFs considered in the LADS study, with the exception of some U.S. Nuclear Regulatory Commission key technical issues that must be considered for the overall repository site (e.g., igneous activity, structural deformation, and seismicity issues).

Table 4-1. References Reviewed by the License Application Design Selection Core Team to Address Design-Related Concerns of Stakeholder and Oversight Groups

Concerned Group	Reference Reviewed by License Application Design Selection Core Team to Address Design-Related Concerns
U.S. Nuclear Regulatory Commission	<i>Issue Resolution Status Report Key Technical Issue: Thermal Effects on Flow</i> (NRC 1997a)
	<i>Issue Resolution Status Report Key Technical Issue: Container Life and Source Term</i> (NRC 1998e)
	<i>Issue Resolution Status Report Key Technical Issue: Unsaturated and Saturated Flow Under Isothermal Conditions</i> (NRC 1997c)
	<i>Issue Resolution Status Report on Methods to Evaluate Climate Change and Associated Effects at Yucca Mountain (Key Technical Issue: Unsaturated and Saturated Flow Under Isothermal Conditions)</i> (NRC 1997d)
	<i>Issue Resolution Status Report Key Technical Issue: Structural Deformation and Seismicity</i> (NRC 1997e)
	<i>Issue Resolution Status Report Key Technical Issue: Repository Design and Thermal-Mechanical Effects</i> (NRC 1997f)
	<i>Issue Resolution Status Report Key Technical Issue: Evolution of the Near-Field Environment</i> (NRC 1998a)
	<i>Issue Resolution Status Report Key Technical Issue: Igneous Activity</i> (NRC 1998b)
	<i>Issue Resolution Status Report Key Technical Issue: Total System Performance Assessment and Integration</i> (NRC 1998c)
	<i>Issue Resolution Status Report Key Technical Issue: Repository Design and Thermal-Mechanical Effects</i> (NRC 1998d)

Table 4-1. References Reviewed by the License Application Design Selection Core Team to Address Design-Related Concerns of Stakeholder and Oversight Groups (Continued)

Concerned Group	Reference Reviewed by License Application Design Selection Core Team to Address Design-Related Concerns
Nuclear Waste Technical Review Board	<i>NWTRB Repository Panel Meeting Overview of Design Selection Process</i> (Snell 1999a)
	<i>Comments Regarding the May 1998 NWTRB Panel Meeting on the Waste Package</i> (Kessler 1998)
	<i>First Report to the U.S. Congress and the U.S. Secretary of Energy</i> (NWTRB 1990)
	<i>Report to the U.S. Congress and the Secretary of Energy, January to December 1996 (1996 Findings and Recommendations)</i> (NWTRB 1997)
National Waste Terminal Storage	"Selection of a Spent-Fuel Disposal Waste Form." <i>Proceedings of the 1981 NWTS Program Information Meeting, November 1981</i> (McBride et al. 1981)
	"Package Materials Screening." <i>Proceedings of the 1981 NWTS Program Information Meeting, November 1981</i> (Moak and Kircher 1981)
Miscellaneous Groups	"Factors Affecting Performance of Engineering Barriers." <i>Proceedings of the 8th International Conference on High-Level Waste Management, May 11-14, 1998</i> (Blink et al. 1998)
	"An Assessment of LWR Spent-Fuel Disposal Options." <i>Proceedings of the 1979 National Waste Terminal Storage Program Information Meeting, October 30 – November 1, 1979 at Columbus, Ohio</i> (DOE 1979)
	<i>Preliminary Assessment of a Technical Basis for Establishing a Retrievability Period</i> (Wilems 1980)
	<i>Containment Barrier Metals for High-Level Waste Packages in a Tuff Repository</i> (Russell et al. 1983)
	<i>Unit Evaluation at Yucca Mountain, Nevada Test Site: Summary Report and Recommendation</i> (Johnstone et al. 1984)
	<i>Repository Sealing Concepts for the Nevada Nuclear Waste Storage Investigations Project</i> (Fernandez and Freshley 1984)
	<i>Nevada Nuclear Waste Storage Investigations Preliminary Repository Concepts Report</i> (Jackson 1984)
	<i>Preclosure Analysis of Conceptual Waste Package Designs for a Nuclear Waste Repository in Tuff</i> (O'Neal et al. 1984)
	<i>Location Recommendation for Surface Facilities for the Prospective Yucca Mountain Nuclear Waste Repository</i> (Neal 1985)
	<i>A Comparative Study of Radioactive Waste Emplacement Configurations</i> (Gram et al. 1985)
	<i>Two-Stage Repository Development at Yucca Mountain: An Engineering Feasibility Study</i> (MacDougall 1985)
	<i>Environmental Assessment Yucca Mountain Site, Nevada Research and Development Area, Nevada</i> (DOE 1986)
	<i>Feasibility Assessment of Copper-Base Waste Package Container Materials in a Tuff Repository</i> (Acton and McCright 1986)
	<i>Cost Comparison of Horizontal and Vertical Waste Emplacement Methods for a Repository in Tuff</i> (Stinebaugh and Robb 1987)
	<i>OGR Repository-Specific Rod Consolidation Study: Effect on Costs, Schedules, and Operations at the Yucca Mountain Repository</i> (O'Brien 1988)
	<i>Yucca Mountain Project Waste Package Design for MRS System Studies</i> (Nelson et al. 1989)
	<i>Mined Geologic Disposal System Requirements Document</i> (YMP 1998)
	<i>Nye County Nuclear Waste Repository Project Office Independent Scientific Investigations Program Annual Report May 1997 – April 1998</i> (Nye County Nuclear Waste Repository Project Office 1998)

In addition, design issues suggested by internal review organizations, including the Repository Consulting Board and the Total System Performance Assessment Peer Review Panel, were reviewed by the LADS core team. The majority of the issues identified by these groups were covered by DAs and DFs included in this study. In a few cases, the LADS core team concluded that a lower level design trade would cover the specific issue. For example, the issue of redundant exhaust ventilation power supplies, fans, and high-efficiency particulate air filters was considered to be covered by a design trade. Design trades address the variations of materials or configurations in the design process in order to assess the variation most likely to enhance postclosure performance and other design goals. It is expected that detailed design trades will be made subsequent to the LADS project to refine the recommended design.

The list of DAs and DFs is shown in Tables 4-2 and 4-3, respectively, with the identification of the source of each item and the actions taken by the LADS core team to refine the list. A discussion of the considerations and actions that resulted in the final list follows the tables.

Table 4-2. Origins of Design Alternatives

Design Alternatives		Origins of Design Alternatives
1	Tailored Waste Package Spatial Distribution	The Viability Assessment (DOE 1998b, Vol. 2, Section 8.2.5) had an alternative termed "waste-specific containment design." The LADS team split this concept into aspects pertaining to locations of specific waste package types and aspects pertaining to tailoring waste package design for specific waste types.
2	Low Thermal Load Design	Viability Assessment (DOE 1998b, Vol. 2, Section 8.2.5).
3	Continuous Postclosure Ventilation Design	Viability Assessment (DOE 1998b, Vol. 2, Section 8.2.5).
4	Enhanced Access Design	Viability Assessment (DOE 1998b, Vol. 2, Section 8.2.5).
5	Modified Waste Emplacement Mode Design	Viability Assessment (DOE 1998b, Vol. 2, Section 8.2.5).
6	Viability Assessment Design	Viability Assessment (DOE 1998b, Vol. 2, Section 4, Section 5).
7	Viability Assessment Design with Options	Viability Assessment (DOE 1998b, Vol. 2, Section 5.3). This DA was considered during selection of the EDAs.
8	Modular Design (Phased Construction)	This DA was added during management review of the Viability Assessment and establishment of the LADS project.

The DAs evaluated in this study include the Viability Assessment design and the Viability Assessment design with options (the options were ceramic coatings, drip shields, and backfill). The Viability Assessment design with options was considered as an EDA candidate based on the Viability Assessment document, and, consequently, did not receive a separate evaluation with the other DAs. Its three component options were also evaluated as individual DFs. Of the six additional DAs evaluated, five were originally identified in the Viability Assessment as interdependent design concepts. The LADS DAs for low thermal load, continuous postclosure ventilation, enhanced access, and modified waste emplacement were essentially identical to alternatives described in the Viability Assessment. The LADS DA for tailored waste package spatial distribution was slightly modified from the alternative proposed in the Viability Assessment. The tailored waste package spatial distribution alternative (the title was changed from waste-specific containment design in the Viability Assessment) included three versions of

Table 4-3. Origins of Design Features

Design Features	Origins of Design Features
Ceramic Coatings	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2).
Drip Shields	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2).
Backfill	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2).
Aging and Blending of Waste	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2). This Viability Assessment option was initially divided into two entries: preemplacement aging and blending. During LADS team review, they were combined.
Continuous Preclosure Ventilation	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2). This option was split into a preclosure feature and a postclosure alternative by the LADS team.
Rod Consolidation	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2).
Timing of Repository Closure	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2).
Maintenance of Underground Features and Ground Support	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2).
Drift Diameter	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2).
Drift Spacing, Waste Package Spacing	Viability Assessment (DOE 1998b, Vol. 2, Section 8.2.2). For a given areal mass loading, the feature of drift spacing also sets waste package spacing.
Waste Package Self Shielding	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2). This was entitled "accessibility" in the Viability Assessment.
Waste Package Corrosion-Resistant Materials (Metal and Ceramic)	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2). This was two features in the Viability Assessment design.
Richards Barrier	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2).
Diffusive Barrier Under the Waste Package	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2). The Viability Assessment entry was captured within this DF and the DF on getter under the waste package.
Getter Under the Waste Package	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2). The Viability Assessment entry was captured within this DF and the DF on diffusive barrier under the waste package.
Canistered Assemblies	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2). This DF also included waste package design-specific aspects from the DA on tailored waste package spatial distribution.
Additives and Fillers	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2).
Ground Support Options	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2). This DF was a combination of two entries in the Viability Assessment table that were examples of specific ground support options. The generalized DF was determined to be more comprehensive by the LADS team.
Near Field Rock Treatment During Construction	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2).
Surface Modifications	Viability Assessment (DOE 1998b, Vol. 2, Section 8, Table 8-2). This DF was a combination of two entries in the Viability Assessment table; one pertaining to the addition of material to the surface and the other pertaining to improving drainage of the surface.
Repository Horizon Elevation	This DF was added during management review of the Viability Assessment and establishment of the LADS project.
Higher Thermal Loading	Viability Assessment (DOE 1998b, Vol. 2, Section 8.2.2). This DF was added by the LADS team.

waste package spatial distribution based on percolation flux, local unsaturated zone transport characteristics, and waste package thermal output. A waste form-specific waste package design option could be applied to other DAs, and, therefore, was considered part of the canistered assemblies DF. The LADS modular design/phased construction DA was added based on a recommendation from U.S. Department of Energy and Management and Operating Contractor management during the Viability Assessment review.

All but one of the DFs included in the LADS study were identified in the Viability Assessment (DOE 1998b, Vol. 2, Section 8.2.2, and Table 8-4). Several of the features identified in the Viability Assessment were rearranged by the LADS core team:

- The Viability Assessment features of aging (preemplacement) and blending (for thermal or criticality considerations) were combined into a DF on aging and blending of waste.
- The Viability Assessment feature of diffusive barrier or getter under the waste package was divided into DFs on diffusive barrier under the waste package and getter under the waste package.
- The Viability Assessment feature of underground features, ground support, and maintenance was divided into DFs on maintenance of underground features and ground support, and ground support options.
- The Viability Assessment features of metal-lined drifts and unlined drifts were combined into a DF on ground support options.
- The Viability Assessment feature of drift spacing was modified into two DFs: drift diameter, and drift spacing and waste package spacing.
- The Viability Assessment features of engineered fill and drainage were combined into a DF on surface modifications.
- The Viability Assessment features of thermal loading and temperature limits were incorporated within both the higher thermal loading DF and the low thermal load DA. The higher thermal loading DF was added during the LADS core team review.
- The Viability Assessment features of horizontal or vertical borehole emplacement were included in the modified waste emplacement mode DA.

Two features identified in the Viability Assessment were deleted by the LADS core team:

- The Viability Assessment DFs of waste package building throughput and waste package size, intended to evaluate the effect on surface facilities of a large number of small waste packages, were assessed to be an intrinsic part of several DAs and DFs that use small waste packages; therefore, they were not considered independently.

The repository horizon elevation DF was added during management review of the Viability Assessment. Locating the potential repository at a different elevation or in multiple levels within the unsaturated zone was evaluated in this DF.

The LADS core team initially considered extending the repository horizon elevation DF to include potential location of the repository in the saturated zone. This consideration was motivated by a mandate to be comprehensive and by recent measurements that indicate that the chemistry of the saturated zone is less oxidizing than previously observed. The Yucca Mountain site was originally suggested as a saturated zone repository site (DOE 1998b, Vol. 1, Section 1.4.2). Subsequent analysis of unsaturated zone hydrology by the U.S. Geological Survey led to movement of the repository horizon to the unsaturated zone (DOE 1998b, Vol. 1, Section 1.4.2; Winograd 1991). For the LADS project, it was concluded that there was not enough new information available to justify a repository design in the saturated zone; the reasons for this conclusion are listed below:

- Limiting the amount of water contacting the waste package has been a continuous goal within the repository design strategy. In the unsaturated zone, the hydrology results in a majority of the waste packages not being exposed to liquid seepage water over the calculated period, which ranges to 1 million years. For a saturated zone repository, elimination of water contact with the waste package would need to rely on a long-lived engineered barrier, such as a clay buffer.
- Limiting the mobilization of radionuclides and their transport within the engineered barrier system was another goal of the repository design strategy. Access to a water-filled environment or the water table would allow greater mobilization and transport of the radionuclides.
- Reduction of radionuclide concentrations during transport from the engineered barrier system to the accessible environment was also a goal of the repository design strategy. Sorption and diffusion into the rock matrix in the unsaturated zone could enhance this goal.
- Controlling the potential for criticality, which would be more likely in a water-filled environment, would be more difficult in the saturated zone.

Based on the above reasons, the repository horizon elevation DF was limited to elevations within the unsaturated zone.

Sections 4.3, 4.4, and 5.1.3 describe these concepts and explain how they were used to create the EDAs.

4.2 DESIGN FEATURE/DESIGN ALTERNATIVE EVALUATION CRITERIA

4.2.1 Introduction

During Phase I of the LADS project, each DF and DA was evaluated against a series of criteria. These criteria represented the information needed to evaluate the DAs and DFs individually, and to help build up the EDAs. Ultimately, they played a role in the evaluation of the EDAs in Phase II.

As discussed in Section 3, the decision process that was followed was one of evaluating multiple alternatives using multiple criteria. In Phase I, the alternatives being evaluated were the DAs

and DFs; in Phase II, the EDAs were evaluated. The criteria for Phase I are discussed in this section; the criteria for Phase II are discussed in Section 5.2. The evaluations against these criteria provided a basis for choosing those DAs and DFs that were most likely to become successful elements of EDAs. Engineering judgment and design experience played a key role in developing the EDAs. Thus, the EDAs were built up, giving due consideration to the criteria against which they were ultimately evaluated in Phase II.

The DA/DF evaluation criteria represented all of the information that was considered at the time the DAs and DFs were evaluated. Prior to the start of Phase II, these criteria were reexamined; additional criteria were included (defense in depth and flexibility), and measurement scales were further defined (see Section 5.2.2). The Phase II criteria were then used to evaluate the EDAs.

Assessments of confidence were made for each of the DA (except DA 7) and DF evaluations. The intent of these assessments was to provide an indication of the uncertainties associated with each evaluation.

4.2.2 Design Feature/Design Alternative Evaluation Criteria

The Phase I evaluation criteria are given below. Some of the evaluation criteria were measured by natural scales (e.g., millirems per year, dollars), while others had constructed scales (e.g., 1 through 5). The evaluation criteria were composed of one or more subcriteria that serve to define the principal criteria. These subcriteria are phrased below in terms of questions that were posed to the lead design engineers. Responses to the questions, as well as their technical justifications, can be found in the respective reports cited in Sections 4.3 and 4.4.

The criterion "environmental considerations" is included below because each DF and DA was evaluated in a preliminary way for environmental effects. Environmental considerations do not discriminate among the DAs and DFs for the purpose of building the EDAs. The environmental considerations of the EDAs were evaluated in Phase II.

4.2.3 Phase I Evaluation Criteria Expressed as Questions

The LADS core team posed questions to the lead design engineers for each DA and DF in order to obtain information related to the Phase I evaluation criteria (CRWMS M&O 1998f). The responses to these questions are given in references cited in Sections 4.3 and 4.4.

Postclosure Performance—What is the peak dose rate to an average individual of a critical group at a distance of 20 km from the repository site and the time of the peak, considering two time periods:

- Less than 10,000 years
- Between 10,000 years and 1 million years

An evaluation of a timing figure of merit of the integrated dose should be included in the evaluation. This evaluation is described in the glossary and given by the equation:

$$\text{Timing Figure of Merit} = [1/(\ln 10^6 - \ln 10^3)] \int_{1ky}^{1My} \dot{D}(t) \frac{dt}{t}$$

where ky is 1,000 years, My is 1 million years, and $\dot{D}(t)$ is the dose rate in year “t.” (The original criteria [CRWMS M&O 1998f] incorrectly indicated a lower limit of integration of zero rather than 1,000 years.) The lower limit was chosen to coincide with the time of assumed juvenile failure and to avoid a divergent integral if the method is applied to a constant background dose rate for comparison.

NOTE: This information should be based on a central estimate (single realization using the expected value of most variables in the total system performance assessment model).

Scale: Quantitative estimates of expected peak dose rate and timing figure of merit in mrem/yr.

Preclosure Performance—What is the assessment of the preclosure performance of the DF or DA on a 1 to 5 scale? Provide an assessment of each question using this scale and a brief (one to two sentence) written basis for the evaluation. The overall evaluation should be the simple average of the assessments for each question.

- Would the DF or DA increase or decrease the probability of a design basis event?
- Would the DF or DA add a design basis event? Is this design basis event bounded by other design basis events?
- Would the DF or DA increase or decrease the consequences of a design basis event?
- Does the DF or DA increase or decrease challenges to the repository safety systems?

Scale: Range from 1 to 5. A 1 indicates that there are significant disadvantages in accommodating design basis events relative to the Viability Assessment design; a 2 indicates that there are moderate disadvantages in accommodating design basis events relative to the Viability Assessment design; a 3 indicates that the design basis events are accommodated comparably to the Viability Assessment design; a 4 indicates that there are moderate advantages in accommodating design basis events relative to the Viability Assessment design; and a 5 indicates that the DF or DA has significant advantages in accommodating design basis events relative to the Viability Assessment design.

What is the preclosure dose rate to the public at the preclosure area boundary?

Scale: Quantitative estimates of expected peak dose rate in mrem/yr.

Assurance of Safety—What is the assessment of the assurance of safety of the DF or DA on a 1 to 5 scale? Provide an assessment of each question using this scale and a brief (one to

two sentence) written basis for the evaluation. The overall evaluation should be the simple average of the assessments for each question.

- Does the DF or DA have uncertainties in postclosure performance?
- What is the potential to reduce the uncertainties by the proposed time of construction and of closure?

Scale: 1 to 5. A 1 indicates that the design provides a low assurance of safety because there are large and significant uncertainties that are unlikely to be reduced, and/or that the design is particularly sensitive to disruptive events; a 2 provides a moderately low assurance of safety compared with the Viability Assessment design; a 3 indicates that there is a reasonable assurance of safety relative to uncertainties and disruptive events similar to the Viability Assessment design; a 4 indicates a moderately high assurance of safety compared with the Viability Assessment design; and a 5 indicates that the design provides a very high assurance of safety compared with the Viability Assessment design because the uncertainties are low or are likely to be significantly reduced, and/or the design is resilient to disruptive events.

Engineering Acceptance—What is the potential for acceptance of the engineering design of the DA or DF in a regulatory environment on a 1 to 5 scale? Provide an assessment of each question using this scale and a brief (one to two sentence) written basis for the evaluation. The overall evaluation should be the simple average of the assessments for each question.

- Can the function of each element in the design be clearly communicated?
- Which of the four elements of the repository safety strategy does it support (limited water contacting waste packages, long waste package lifetime, low rate of release of radionuclides from breached waste packages, radionuclide concentration reduction during transport from the waste packages)?
- Does the engineering analysis follow accepted methods?
- Is the postclosure function simple to demonstrate?
- Are there regulatory and/or engineering precedents for the design?
- What is the availability of qualified data to support the design likely to be in the proposed License Application time frame?
- Is the design constructable with proven methods?
- Are any high-level design goals for the Monitored Geologic Repository (such as the goals listed in the controlled design assumptions document [CRWMS M&O 1998a]) violated by the use of this design?

Scale: 1 to 5. A 1 indicates that the design has a very low potential for acceptance compared with the Viability Assessment design; a 2 indicates a moderately low potential for acceptance compared with the Viability Assessment design; a 3 indicates a moderate potential for

acceptance similar to the Viability Assessment design; a 4 indicates a moderately high potential for acceptance compared with the Viability Assessment design; and a 5 indicates a very high potential for acceptance compared with the Viability Assessment design.

If applicable, what is the effective lifetime of the feature or major component of the alternative in supporting the particular element of the repository safety strategy?

Scale: Quantitative estimate of the effective lifetime in years, or expected distribution of lifetime, if available.

Construction, Operations, and Maintenance—Are there any particular difficulties or advantages that the DF or DA has relative to the Viability Assessment design for the following construction, operations, and maintenance characteristics:

- Would the DA or DF increase or decrease worker radiation safety and/or industrial safety?
- Would the DA or DF increase or decrease reliability, availability, maintainability, and inspectability of manufactured and constructed items?
- Would the DA or DF increase or decrease throughput capability?
- Would the DA or DF increase or decrease the ability to conduct performance confirmation activities?

Scale: 1 to 5. A 1 indicates that the design has significant disadvantages or difficulties in construction, operations, and maintenance compared with the Viability Assessment design; a 2 indicates moderate disadvantages or difficulties in construction, operations, and maintenance compared with the Viability Assessment design; a 3 indicates that the construction, operations, and maintenance are similar to those of the Viability Assessment design; a 4 indicates moderate advantages in construction, operations, and maintenance compared with the Viability Assessment design; and a 5 indicates that there are significant advantages in construction, operations, and maintenance compared with the Viability Assessment design.

Schedule—For the DF or DA, how does the proposed License Application schedule compare to that for the Viability Assessment design? Please provide a brief (one to two sentence) written basis for the evaluation.

Scale: Difference in time required for site characterization, design, licensing, and construction relative to the Viability Assessment design.

Cost—What is the difference in estimated total cost relative to the Viability Assessment design? (Conceptual design estimating is applicable [± 50 percent].) Provide a brief (one to two sentence) written basis for the evaluation.

Scale: Cost in 1999 dollars. Costs that occur significantly later than the current schedule for the Viability Assessment design should be noted where possible.

Environmental Considerations—What are the environmental considerations associated with the DF or DA relative to the Viability Assessment design?

4.2.4 Confidence Assessment

The evaluations of the DAs and DFs against the Phase I criteria included both quantitative (e.g., postclosure performance and cost) and qualitative evaluations (e.g., engineering acceptance and worker safety). In either case, there were uncertainties. To provide an indication of the degree of uncertainty, the confidence associated with each evaluation was assessed by the lead design engineers for each DA and DF (CRWMS M&O 1999ii). The following scale was used to assess confidence:

- High level of confidence (A): The assessment is readily supported, defensible, and is not subject to much uncertainty.
- Moderately high (B): The assessment is supportable, reasonably defensible, and is only subject to moderate uncertainty.
- Moderate (C): The assessment is supportable, reasonably defensible with some possible weaknesses, and is subject to moderate uncertainty.
- Moderately low (D): The assessment is not well supported, has some weaknesses in terms of defensibility, and is subject to uncertainty.
- Low (E): The assessment is not well supported, has significant weaknesses in terms of defensibility, and is subject to considerable uncertainty.

Unlike the evaluation criteria, the confidence scales were independent of the Viability Assessment design. That is, the confidence scale was in an absolute framework, rather than relative to the Viability Assessment design. For each DF and DA, two assessments were made for postclosure performance: one by the lead design engineer and another by the performance assessment analyst. Confidence assessments are found in the references cited in Sections 4.3 and 4.4.

4.3 DESIGN ALTERNATIVE DESCRIPTIONS

DAs are defined in the list in Section 4.1. DA 1 through DA 5 focus on the engineered barrier system, while DA 8 focuses on the surface facilities. Brief descriptions of DA 6 (the Viability Assessment design) and DA 7 (the Viability Assessment design with options) are included in this section for completeness.

4.3.1 Design Alternative 1—Tailored Waste Package Spatial Distribution

This DA addressed the position and placement of specific types of waste in the repository block emplacement drifts to determine if the postclosure isolation performance of the repository can be improved. The Viability Assessment design emplaced the waste packages in the order received, with the only restrictions being the total amount of heat per acre and adjacent package heat considerations. This DA evaluation identified combinations of site characteristics and waste

forms/packages that would provide improved waste isolation performance and that practicable engineering could support (Figures 4-1 through 4-5). More information is contained in the DA 1 evaluation report (CRWMS M&O 1999cc).

4.3.2 Design Alternative 2—Low Thermal Load

The low thermal load DA limits the temperature rise of the drift wall and host rock. Thermal loading is defined as the amount of heat from radioactive decay produced in a unit area. This heat energy is usually measured in kilowatts per acre or watts per square meter. However, it can also be expressed in units of mass of heavy metal per area. A low thermal load of 25 metric tons of heavy metal (MTHM)/acre was evaluated in this study. The low thermal load was achieved by spreading the waste over a larger emplacement area (10 km² instead of 3 km²). The primary option used the same waste packages and spacing as the Viability Assessment design, but increased the drift spacing. A second option used smaller waste packages than the Viability Assessment design (Figure 4-6). More information is contained in the DA 2 evaluation report (CRWMS M&O 1999dd).

4.3.3 Design Alternative 3—Postclosure Ventilation

The postclosure ventilation DA identified a series of conceptual designs aimed at utilizing ventilation in the emplacement drifts during the postclosure period. The most promising concepts were selected for evaluation. The expected benefit provided by postclosure ventilation was improved waste package performance. Improved performance could be achieved by limiting the amount of water and/or humidity contacting the waste packages, which would reduce corrosion. The evaluations showed that a ventilated repository reduces the emplacement drift air temperature, as well as the relative humidity, rock saturation (hence, seepage into the drift), and rock temperature (Figures 4-7 through 4-9). More information is contained in the DA 3 evaluation report (CRWMS M&O 1999ee).

4.3.4 Design Alternative 4—Enhanced Access Design

This DA investigated the possibility and the outcome of providing sufficient radiation shielding for the waste packages to allow personnel access during handling and inspection operations. This, in turn, would simplify component design and operations. Access to the emplacement drifts would be provided so personnel could execute performance confirmation activities. These performance confirmation tasks would be needed to verify design performance through measurements that must be taken in situ (e.g., design analysis, fabrication inspections, or demonstration tests), but whose necessity may not be known until the final design stage of this project. More information is contained in the DA 4 evaluation report (CRWMS M&O 1999ff).

4.3.5 Design Alternative 5—Modified Waste Emplacement Mode Design

In this DA, unshielded waste packages were placed in a configuration where the repository's natural or engineered barriers would provide the personnel shielding. This alternative is similar to the enhanced access design (DA 4) in that personnel could access areas near the waste packages, but in this DA the waste packages do not have to be shielded. Various configurations for accomplishing the shielding using the natural and engineered barriers were considered

(Figures 4-10 through 4-14). More information is contained in the DA 5 evaluation report (CRWMS M&O 1999gg).

4.3.6 Design Alternative 6—Viability Assessment Design

The complete description of the Viability Assessment design is presented in the Viability Assessment (DOE 1998b), specifically in Volume 2. A brief description is included here to facilitate comparisons. The Viability Assessment design addresses the surface facilities, subsurface facilities, and waste package design, which are described in the following paragraphs.

The surface facilities would be designed to receive the spent nuclear fuel and high-level radioactive waste shipments, then prepare and package the wastes for underground emplacement (Figure 4-15). They would also support the excavation, construction, loading, and ventilation of the repository tunnels. The entire surface layout would cover about 100 acres.

Spent nuclear fuel waste packages would generally hold 21 pressurized-water reactor or 44 boiling-water reactor spent nuclear fuel assemblies. The weight of the package, when loaded with waste and sealed, would be about 76 tons. The heaviest packaged waste form would be naval spent nuclear fuel in sealed, disposable canisters weighing about 49 tons each; the total weight of the sealed naval waste package would be 91 tons.

The waste package for the Viability Assessment design has an inner barrier of 2-cm thick Alloy-22, surrounded by an outer barrier of 10-cm thick A516 carbon steel. The outer barrier cylindrical wall extends past the lids, forming a reduced-thickness skirt at either end of the waste package. This feature facilitates handling and serves to improve the package's resistance to damage by acting as a shock absorber should the waste package be dropped on end.

The underground repository would consist of about 107 km of emplacement drifts. The main tunnels would be designated for moving workers, equipment, and waste packages, with ventilation side tunnels to provide air. Two gently sloping access ramps and two vertical ventilation shafts would connect the underground and surface areas.

The repository subsurface layout was designed to accommodate the emplacement of 70,000 MTHM at an areal mass loading of 85 MTHM/acre. This layout would include an estimated contingency capacity of 15 percent. No waste packages would be emplaced in locations where inspections have determined that the ground conditions are unsuitable.

The waste emplacement block would be at least 200 m below the surface and at least 100 m above the water table. The block would cover about 740 acres and would accommodate about 11,000 waste packages. The waste packages would be located along the centerline of the emplacement drifts, which would run in an east-west direction. The emplacement drifts would be accessible, fully lined with concrete, and have a maintainable service life of at least 150 years. An additional area of 107 acres has been identified as a contingency area if some drifts in the main block are unacceptable or if they are needed to accommodate higher thermal output packages.

One or all of the waste packages may have to be retrieved from an emplacement drift during preclosure. Retrieval would begin by blast cooling the drift with air to lower the temperature

to 50°C. Using this system, waste packages could be retrieved from only one emplacement drift at a time. The limited capacity of the two ventilation exhaust ducts would limit the total capacity of the subsurface ventilation high efficiency particulate air filter system.

4.3.6.1 Evaluation Summary

DA 6 (the Viability Assessment design) was discussed in the Viability Assessment (DOE 1998b). No specific evaluation using the evaluation criteria of Section 4.2 was performed. Instead, DA 6 is the standard against which the DFs and other DAs were evaluated.

4.3.6.2 Confidence Assessment Summary

In order to determine the level of confidence in the information related to the Viability Assessment design (DA 6), the confidence of individuals having significant roles in the development of the Viability Assessment design was elicited. Their comments regarding the confidence level comprise this confidence assessment summary.

Postclosure Performance—No lead design engineer was assigned, since the Viability Assessment design was complete. The performance assessment analyst's confidence score was C. Seepage was the most important parameter (up to 50 percent of the output), and a wide range of values was considered. The use of concrete introduced uncertainties because it had been assumed that seepage would not touch any concrete before reaching the waste packages. The saturated zone modeling and dilution factors should be improved.

Preclosure Performance—The confidence in preclosure performance was rated B. The design basis events have been evaluated in some detail, and there were only minor uncertainties.

Assurance of Safety—The confidence score was moderately high, a B, although there does not appear to be much defense in depth. Many uncertainties have been considered.

Engineering Acceptance—The confidence score was D. There were significant model uncertainties and limited data were available.

Construction, Operations, and Maintenance—The confidence score was C. There were uncertainties in remote operations and repair.

Schedule—The confidence score for the design stage schedule was D+; the confidence score for the emplacement stage was B.

Cost—The confidence score was A. A considerable amount of study has been done.

4.3.7 Design Alternative 7–Viability Assessment Design with Options

This DA consists of the Viability Assessment design (Section 4.3.6) combined with three options described in this report as DFs (see Figure 4-16):

- Ceramic coatings (see Section 4.4.1)
- Backfill (see Section 4.4.2)
- Drip shield (see Section 4.4.3)

4.3.8 Design Alternative 8–Modular Design/Phased Construction

This DA investigated the effects of separating the Waste Handling Building, the Carrier Preparation Building, and the subsurface repository into multiple modules, structures, or phases to be constructed over time. Direct support facilities such as the Waste Treatment Building, the balance of the plant support facilities, and any additional facilities required for the support of early receipt or storage were included in the evaluation.

An integrated design is one in which each building phase (after the original phase) depends on an earlier phase for shared operations, and any phase following the original phase cannot operate independently. A modular design is one where follow-up building phases can operate independently of the original phase.

Six alternative design concepts were evaluated to determine the impact on waste throughput quantities. These concepts were analyzed to determine how they performed in relation to funding constraints, waste receipt/storage, and emplacement rates. Subsurface construction and phasing to meet estimated emplacement rates were also evaluated to determine the most effective method of meeting the study objectives. More information is contained in the DA 8 evaluation report (CRWMS M&O 1999hh).

4.4 DESIGN FEATURES DESCRIPTIONS

The DFs discussed in this section are listed in Section 4.1. In general, a DF is a particular element or attribute of the repository for which postclosure performance and other factors can be evaluated independently of a specific repository design or other DFs. An individual DF may encompass separate, discrete concepts or a continuous range of parametric values.

DFs include both physical and mechanical enhancements, as well as operational and programmatic enhancements. For the purpose of a comparative evaluation, each DF was evaluated, to the extent possible, within the reference frame of the Viability Assessment design. The following sections describe the DFs that are considered in this report. These descriptions include the anticipated advantages of the DFs. Results of the evaluations, including the potential disadvantages, are discussed in the referenced evaluation reports.

4.4.1 Ceramic Coatings

The application of a ceramic material to a waste package would prevent water from contacting the outer metal barrier for a long period of time. There are several thermal processes that produce high-density coatings on metals, and the range of materials that can be applied is

extensive. The coating materials being considered include magnesium aluminate spinel, aluminum oxide, titanium oxide, and zirconia-yttria. Spinel is the leading candidate material. It has many natural analogues, performs very well in a radioactive environment, and exists in its lowest energy state as an oxide, which allows the material to function in an oxidizing environment. The coating would be applied to the waste package outer barrier with a thermal-spray process (Figure 4-17). More information is contained in the ceramic coatings evaluation report (CRWMS M&O 1999b).

4.4.2 Backfill

Backfill consists of granular material (such as sand or gravel). Backfill can be placed over the waste packages to protect them from rockfall (Figure 4-18). The waste packages would generate heat after emplacement, and this heat would tend to drive water away from the emplacement location. Backfill would act as insulation for the waste packages, keeping the waste packages hotter. The emplacement areas would then stay hotter longer, which would retard the onset of waste package corrosion by delaying the onset of water contacting the waste packages. The waste packages would gradually cool off and become vulnerable to corrosion caused by water and corrosive minerals dissolved in the water. More information is contained in the backfill evaluation report (CRWMS M&O 1999c).

4.4.3 Drip Shield

A drip shield is a rigid structure that diverts water away from the waste packages. Corrosion-resistant metals (Alloy-22), metals with ceramic coatings, and monolithic ceramics have been considered as drip shield materials. Two drip shield options are being considered: a drip shield under the backfill (Figure 4-19) and a drip shield over the backfill (Figure 4-20). More information is contained in the drip shield evaluation report (CRWMS M&O 1999d).

4.4.4 Preemplacement Aging and Blending of Waste

The preemplacement aging and blending DFs were evaluated to determine if they could provide thermal performance benefits for the potential repository at Yucca Mountain. Aging reduces the total thermal energy that must be accommodated by the repository and blending reduces the variability in the distribution of the thermal energy in the repository drifts. Proposed benefits of these DFs are improved rock stability and retardation of waste package degradation. The aging feature may require the construction of a surface storage facility. The blending feature would result in an increase in the size of the pool at the Waste Handling Building. More information is contained in the preemplacement aging and blending evaluation report (CRWMS M&O 1999e).

4.4.5 Continuous Preclosure Ventilation

During preclosure, a ventilation system would deliver a specified volume of air to the emplacement drifts containing waste packages. This continuous ventilation would reduce air and drift temperatures, and carry away moisture that could otherwise increase corrosion. The host rock would remain drier and cooler during preclosure compared to a repository (such as the Viability Assessment design) where little ventilation was provided. More information is contained in the continuous preclosure ventilation evaluation report (CRWMS M&O 1999f).

4.4.6 Rod Consolidation

Pressurized-water reactor and boiling-water reactor fuel assemblies have fuel rods arranged in regular square arrays with rod-to-rod separations consistent with those needed for power reactor operation (Figure 4-21). Rod consolidation involves taking the fuel rods out of the arrays and bringing them into direct contact with one another. This reduces the volume taken up by fuel assemblies and allows the capacity of waste packages to be increased and/or the size of waste packages to be reduced. The fuel assemblies are consolidated by removing the fuel rods from the assembly and placing them in a canister. Each canister may contain fuel rods from one or more fuel assemblies (Figure 4-22). These canisters are then loaded into the waste package. Non-fuel components (e.g., control rods, channels, etc.) are separated from the fuel assemblies for disposal by other methods. The remainder of the assembly hardware is disposed of separately. The consolidation process may occur in a pool or shielded dry environment. More information is contained in the rod consolidation evaluation report (CRWMS M&O 1999g).

4.4.7 Timing of Repository Closure and Maintenance of Underground Facilities and Ground Support

The timing of the repository closure DF addresses the changes in performance criteria that result from consideration of a monitoring phase of up to 300 years, as opposed to the 100-year period from initiation of waste emplacement used in the Viability Assessment design. Included in the evaluation were requirements to facilitate keeping the repository open for an additional 200 years, the related cost implications, and a risk assessment. The maintenance of underground facilities and ground support DFs were included in this evaluation because the two features are interrelated. Underground facilities and ground support affect the level of maintenance in the emplacement drifts that is needed to accommodate an extended long-term repository service life (Figure 4-23). The benefit of a maintenance program is that it can reduce the risk of rockfall within the emplacement drifts. The evaluation included an assessment of the effect an extended service life would have on the ground support systems under rock stress and thermal and seismic loads. Two operational concepts (options) of the DF were evaluated for economical and functional comparison. More information is contained in the timing of repository closure and maintenance of underground facilities and ground support evaluation report (CRWMS M&O 1999h).

4.4.8 Drift Diameter

The diameter of the emplacement drift is influenced by a number of primary DFs. Heat management strategies, emplacement mode, and emplacement equipment are major influencing factors. The size of the emplacement drift may directly affect design considerations such as opening stability (rockfall potential), the extent of the mechanically induced disturbed zone, and the amount and location of moisture seepage into the drifts. These design considerations may affect the repository performance. The drift diameter for the Viability Assessment design is 5.5 m. A range of drift diameters from 3.5 to 7.5 m were considered (Figure 4-24). More information is contained in the drift diameter evaluation report (CRWMS M&O 1999i).

4.4.9 Waste Package Spacing and Drift Spacing

Waste package spacing is the distance between the ends of two consecutive waste packages. Drift spacing is the distance between two consecutive drifts. Complementary arrangement of waste package spacing and drift spacing could enhance the drying of adjacent rock and decrease the amount of water that could contact the waste package. This is accomplished by increasing the temperatures within the drifts for a longer period of time. The higher temperatures in the drift, caused by a closer spacing of waste packages, would prolong the period in which the temperature would be above the boiling point of water. This would keep the drifts drier longer. Two waste package spacing options, 0.1 m and 1.0 m, were considered; these spacings are closer than that of the Viability Assessment design. Drift spacing would be increased beyond that of the Viability Assessment design to accommodate the heat load associated with close waste package spacing. The net result would be no change in thermal loading of the repository (Figure 4-25). More information is contained in the waste package spacing and drift spacing evaluation report (CRWMS M&O 1999j).

4.4.10 Waste Package Self-Shielding

The Viability Assessment design includes the transportation and emplacement of waste packages using remote controlled equipment. Waste package self-shielding, coupled with ventilation to lower the temperature in the drifts, would allow personnel access to the drifts during the preclosure period by reducing emitted radiation to acceptable levels. More information is contained in the waste package self-shielding evaluation report (CRWMS M&O 1999k).

4.4.11 Waste Package Corrosion-Resistant Materials (Metal and Ceramic)

The Viability Assessment waste package design considered two concentric waste package barriers. This consisted of an outer barrier made of 100-mm thick A516 carbon steel corrosion-allowance material and an inner barrier made of 20-mm thick, nickel-based Alloy-22 corrosion-resistant material. A possible enhancement to the Viability Assessment waste package design is to replace the corrosion-allowance material with a second corrosion-resistant barrier (Figure 4-26). More information is contained in the waste package corrosion-resistant materials evaluation report (CRWMS M&O 1999l).

4.4.12 Richards Barrier

A Richards Barrier is a special type of backfill consisting of a fine-grained material, such as sand, covering a coarse-grained material, such as gravel. The coarse-grained material, in turn, covers the waste package, with the fine-grained material acting as a cap or cover for the coarse-grained material (Figure 4-27). The Richards Barrier uses the difference in permeability between the two backfill materials to divert water. Water entering the emplacement drift would flow in the fine-grained material and not enter the coarse-grained material. The water would travel to the edge of the fine-grained material and reenter the surrounding rock mass through cracks. More information is contained in the Richards Barrier evaluation report (CRWMS M&O 1999m).

4.4.13 Diffusive Barrier Under the Waste Package/Getter Under the Waste Package

The diffusive barrier component is a loose, dry, granular material placed in the intervening space beneath each waste package and above the bottom of the emplacement drift to a sufficient depth and degree of compaction that would form a restrictive barrier to seepage (Figure 4-28). The getter component, a fine-grained material with an affinity for radionuclides, would be mixed with a matrix material and dumped into the invert recess. The combined material would be placed around the structural supports of the waste package to eliminate voids when the waste package is emplaced (Figure 4-29). More information is contained in the diffusive barrier under the waste package/getter under the waste package evaluation report (CRWMS M&O 1999n).

4.4.14 Canistered Assemblies

Placing spent nuclear fuel assemblies in canisters before inserting them into the waste package could provide an additional barrier and further limit mobilization of radionuclides if the waste package is breached. Three general concepts follow: Canisters could be designed to hold individual fuel assemblies (Figure 4-30). Canisters could be designed to hold a few assemblies (Figure 4-31). A large canister could be designed to hold multiple fuel assemblies and fit one canister per waste package (Figure 4-32). More information is contained in the canistered assemblies evaluation report (CRWMS M&O 1999o).

4.4.15 Additives and Fillers

Waste package additives and fillers (henceforth referred to simply as "fillers") are materials that can be placed into a loaded waste package to fill the remaining void spaces. These materials may have the following benefits for performance of the engineered barrier system: 1) retardation of radionuclide release from a breached waste package by adsorbing radionuclides and providing resistance to advective transport; 2) displacement of the moderator from the interior of the waste package to provide additional defense in depth for criticality control; and 3) limiting the amount of oxygen available for waste form alteration. In addition, various waste package filler options may provide benefits such as serving as a mechanical packing to inhibit movement of the waste form within the package, creating a barrier to the release of particulate radionuclides during a design basis event, or providing cathodic protection of fuel and basket material (Figure 4-33). More information is contained in the additives and fillers evaluation report (CRWMS M&O 1999p).

4.4.16 Ground Support Options

Ground support options for the emplacement drifts were evaluated to determine the potential these options may have for enhancing repository performance. Under consideration are the functional requirements for ground support, the use of either concrete (Figure 4-34) or steel-lined systems (Figures 4-35 and 4-36), and the feasibility of using an unlined ground support system using grouted rock bolts (Figure 4-37). More information is contained in the ground support options evaluation report (CRWMS M&O 1999q).

4.4.17 Near-Field Rock Treatment During Construction

The function of rock treatment is to limit the amount of water that can seep into the drift. The treatment would consist of injecting low-permeability grout into the cracks in a portion of the rock overlying each drift in order to lower the hydraulic conductivity of the rock in the treated zone (Figure 4-38). This would decrease seepage into the drift and thus reduce the amount of water that may contact the waste packages during postclosure. To meet seepage criteria, the rock treatment would be required to perform while seepage toward the emplacement drifts occurs. More information is contained in the near-field rock treatment during construction evaluation report (CRWMS M&O 1999r).

4.4.18 Surface Modifications

Surface modifications may be a means to significantly reduce or eliminate the amount of water that could seep into the mountain from the surface and reach the waste packages. Two modification options were considered. The first option (alluvium option) is to alter the ground surface to encourage natural removal of water to the atmosphere by evaporation from the ground surface and deep-water removal by transpiration from plants. The second option (drainage option) is to alter the surface drainage to promote the rapid runoff of surface water by removing the thin layer of alluvium on the hilltops and slopes to expose the bedrock. More information is contained in the surface modifications evaluation report (CRWMS M&O 1999s).

4.4.19 Repository Horizon Elevation

Two basic design concepts were evaluated for the repository horizon elevation feature. The first concept was to relocate the repository to a higher elevation. This higher elevation would be excavated in a single lithophysal unit, specifically the upper lithophysal unit. The second concept was utilization of a two-tier repository. This concept could allow for repository expansion should a decision be made to increase the waste inventory, provide performance improvements through thermal hydraulic effects, and increase flexibility in waste package emplacement strategies. More information is contained in the repository horizon elevation evaluation report (CRWMS M&O 1999t).

4.4.20 Higher Thermal Loading

This feature would increase the thermal loading of the repository by placing the waste packages closer together, thereby increasing the density of heat sources in the repository. Although the total heat would not increase, it would be more concentrated because the repository would occupy a smaller area. This closer packing of waste packages could be done in one of three ways (Figure 4-39). The emplacement drifts could be excavated closer to one another. The waste packages could be placed closer together within each drift, with the emplacement drifts at their original reference spacing. The third possibility combines the first two options, resulting in closely spaced waste packages in closely spaced drifts. In all cases, the increased number of waste packages in a given area would create a higher concentration of heat, resulting in a higher thermal load to a given area of the repository. More information is contained in the higher thermal loading evaluation report (CRWMS M&O 1999u).

Figure 4-1. Waste Packages Distributed by Waste Package Condition

Figure 4-2. Waste Packages Distributed by Thermal Output

Figure 4-3. Waste Packages Distributed by Radionuclide Content

Figure 4-4. Mixed Waste Package Distribution
(differently shaded waste packages indicate waste packages with different characteristics)

Figure 4-5.. Regionally Tailored Waste Package Distribution
(differently shaded waste packages
indicate waste packages with different
characteristics)

Figure 4-6. Low Thermal Load Versus Viability Assessment Load

Bow Tie Concept

Figure 4-7. Postclosure Ventilation, Bow Tie Concept

Figure 4-8. Postclosure Ventilation, Triangle Concept

Figure 4-9. Open-Loop Postclosure Ventilation
(warm air exhaust is at a higher elevation
than cold air intake)

Figure 4-10. Vertical Borehole Emplacement

Figure 4-11. Horizontal Borehole Emplacement
(the inclined borehole will drain
into the drift)

Figure 4-12. Trench Emplacement

Figure 4-13. Alcove Emplacement

Figure 4-14. Short Cross-Drift Emplacement
(the cross-drifts are at 30° angles to the access drifts)

Figure 4-15. Viability Assessment Design

Figure 4-16. Viability Assessment Design with Options

Figure 4-17. Ceramic Coating on Waste Package

Figure 4-18. Typical Backfill Over Waste Package

Figure 4-19. Drip Shield Under Backfill

Figure 4-20. Drip Shield Over Backfill

Figure 4-21. Typical Pressurized-Water Reactor Fuel Assembly

Figure 4-22. Consolidated and Canistered Fuel Rods in Waste Package

Figure 4-23. Concept of Ground Support Maintenance

Figure 4-24. Different Drift Diameters

Figure 4-25. Point Load and Line Load Configurations

Figure 4-26. Waste Package with Dual Corrosion-Resistant Materials

Figure 4-27. Richards Barrier

Figure 4-28. Diffusive Barrier Under Waste Package

Figure 4-29. Getter Under Waste Package

Figure 4-30. Individually Canistered Fuel Assemblies

Figure 4-31. Canister with Multi-Fuel Assemblies

Figure 4-32. All Fuel Assemblies in a Single Canister

Figure 4-33. Two Filler Options

Figure 4-34. Concrete Ground Support System

Figure 4-35. Steel Set Ground Support System

Figure 4-36. Welded Wire Fabric Mesh Ground Support System

Figure 4-37. Grouted Rock Bolt Ground Support System

Figure 4-38. Near Field Rock Treatment Concept

Figure 4-39. Different Waste Package Spacings for Higher Thermal Load

Figure 4-21. Typical Pressurized-Water Reactor Fuel Assembly

Figure 4-22. Consolidated and Canistered Fuel Rods in Waste Package

Figure 4-23. Concept of Ground Support Maintenance

Figure 4-24. Different Drift Diameters

Point Load

Line Load

Figure 4-25. Point Load and Line Load Configurations

Figure 4-26. Waste Package with Dual Corrosion-Resistant Materials

Figure 4-27. Richards Barrier

Figure 4-28. Diffusive Barrier Under Waste Package

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Figure 4-35. Steel Set Ground Support System

Figure 4-36. Welded Wire Fabric Mesh Ground Support System

Figure 4-37. Grouted Rock Bolt Ground Support System

Figure 4-38. Near Field Rock Treatment Concept

Figure 4-39. Different Waste Package Spacings for Higher Thermal Load

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5. ENHANCED DESIGN ALTERNATIVES

Enhanced design alternatives (EDAs) are design concepts that have been enhanced by the inclusion of multiple design features (DFs). In Phase I, a number of design alternatives (DAs) were considered in their simplest state; the goal was to consider a basic design concept (e.g., low-temperature design) without additional DFs to enhance its performance, operability, etc. Likewise, the DFs were considered as “one-off” changes to the Viability Assessment (DOE 1998b) design, without considering the potential implications of the DF being associated with a different DA. Phase I definitions and associated analyses were intended to provide comparative information among the DAs and DFs for evaluation against Phase I evaluation criteria. By placing all DAs and DFs on an even playing field (i.e., using the same assumptions), it was possible to compare and evaluate them.

As discussed in Section 3, EDAs are the conceptual designs evaluated in Phase II of the License Application Design Selection (LADS) process. They were developed with a knowledge of the evaluation criteria in Phases I and II. The EDAs were not subject to the constraints associated with Phase I, and could be developed with any number or combination of DAs and DFs. The designations of design concepts as either DA or DF, which helped in the organization of the effort in Phase I, were not given any significance in the EDA development process. Hence, two DAs could be combined if deemed appropriate, or multiple DFs could be associated with any number of DAs.

It is important to remember that the build-up of the EDAs was a conceptual design process. The analyses and evaluations of the DAs and DFs conducted as part of Phase I provided valuable information, but the development of EDAs also required professional engineering judgment based on experience in conceptual design. General design concepts, rather than detailed design specifications, are the fundamental elements. Design concepts might include features such as aging, blending, ventilation, and rod consolidation, with only descriptive qualifiers for each concept (e.g., ventilate the emplacement drifts at 2 to 5 m³/s for 50 years). Following this conceptual design stage of the LADS process, the recommended design would be refined and optimized. The development of the License Application design will necessarily be an iterative process, involving newly acquired scientific information, evolution of performance assessment models, and design evolution starting from the design recommended in this report.

Candidate EDAs were developed during a 10-day workshop, described below. Its purpose was to encourage and facilitate the creative conceptual design process. Multiple iterations of the design concepts as they were developing, followed by peer feedback, allowed a structured brainstorming of ideas and the eventual identification of strong candidate EDAs.

The information presented in this section is structured as follows: Section 5.1 describes the development of the EDAs. Sections 5.1.1 through 5.1.3 document the chronology and evolution of the EDAs, Section 5.1.4 details the selection of the five EDAs to be considered in Phase II, Section 5.1.5 gives the standard features and design rationale for the selected EDAs, Section 5.1.6 summarizes how the DAs were used in the selected EDAs, and Section 5.1.7 lists the DFs not selected for future consideration. Section 5.2 gives the criteria used to evaluate the EDAs. Section 5.3 presents evaluation summaries of the selected EDA designs and their respective costs.

5.1 ENHANCED DESIGN ALTERNATIVE DEVELOPMENT

The major objectives of the EDA development process were to: 1) arrive at a reasonable number of EDAs for further detailed evaluation; 2) build up EDAs likely to be rated highly against the Phase II evaluation criteria; and 3) develop a diverse set of EDAs that, as a group, represented a range of design types.

To accomplish these objectives, a process was designed to build up EDAs with a high potential for success, rather than eliminate possible EDAs. The process should be viewed as working to identify a set of successful EDAs, not as screening and eliminating possible combinations of DFs and DAs to arrive at the best set of EDAs. This development process, which is common in conceptual design exercises, avoids identifying an EDA that would not rate well against the Phase II evaluation criteria. The information developed for the DAs and DFs, in addition to other information developed for the Yucca Mountain Site Characterization Project, was used as much as possible. Engineering judgment based on past experience, however, was essential to the EDA candidate selection process.

Candidate EDAs were developed during a 10-day workshop held January 4 to 15, 1999. Workshop participants included the LADS core team, lead design engineers for the DAs and DFs, and performance assessment leads. Observers from the Management and Operating Contractor, the U.S. Department of Energy (DOE), the Nuclear Waste Technical Review Board, and the U.S. Nuclear Regulatory Commission were also present (Hastings 1999). The LADS core team selected the set of EDAs to be analyzed in Phase II. This decision was reached through a team consensus.

5.1.1 Information Available Prior to the Workshop

The following information was available at the time of the EDA development workshop:

- The overall decision process (see Section 3)
- Phase I DA/DF Evaluation Criteria (see Section 4.2)
- Evaluations of each DA and DF according to the Phase I evaluation criteria (per guidance provided to DA and DF leads)
- Assessments of confidence in the evaluations against the evaluation criteria
- Descriptions of total system performance assessment abstractions and assumptions for the DAs and DFs
- Total system performance assessment calculations for the DAs and DFs: central (single valued) estimates of dose rate within 10,000 years, peak dose rate over the period up to 1 million years, and the timing figure of merit (see Section 4.2.3)
- Defense-in-depth methodology as demonstrated by the Viability Assessment design

- Draft QAP-3-5 reports prepared for each DA and DF, providing engineering analyses, concept of operations, and evaluations against the Phase I evaluation criteria

To assist the LADS team, a table summarizing the information developed for the DAs and DFs in the draft QAP-3-5 reports was prepared (see Table 5-1). Expressions of confidence in each assessment were included in the summary table; decision analysis team members obtained these confidence assessments from the lead design engineers before the workshop (see Section 4.2.4). While originally these confidence assessments were constructed on a five-point numeric scale (1 to 5), these scores were later converted to letter scores (E to A) to avoid confusion with the evaluation criteria assessment scores (see Section 4.2.4). During early workshop presentations, the LADS core team was given the opportunity to ask questions of the lead design engineers, particularly regarding the technical bases for assessments. Table 5-1 shows the assessments provided prior to the workshop. The information in Table 5-1 is the result of the preliminary evaluations and confidence assessments that were available prior to the workshop and presented during the workshop (Hastings 1999). It is recognized that some modifications were made to the assessments by the lead design engineers following the workshop but prior to their finalization. These modifications, however, did not impact the conclusions of the workshop. The technical bases for the evaluation criteria and confidence assessments for each DA and DF are documented in their respective reports (CRWMS M&O 1999b through 1999u, and CRWMS M&O 1999cc through 1999hh).

5.1.2 Enhanced Design Alternative Workshop Process

The 10-day workshop to develop the candidate EDAs was organized to include both general sessions and breakout sessions, in which three EDA teams (called “breakout teams”) focused on different design concepts. An iterative process was used whereby the breakout teams developed candidate EDAs that were examined in a general session, followed by additional refinement by the breakout teams. At the final general session, the LADS core team identified the candidate EDAs to be further considered.

5.1.2.1 Review of Individual Design Alternative and Design Feature Evaluations (General Session on Days 1, 2, and 3)

During the first three days of the workshop, the lead design engineers summarized their draft QAP-3-5 reports, including the evaluations of DAs and DFs according to the evaluation criteria. These presentations included both quantitative assessments (e.g., postclosure performance measures) and qualitative assessments (e.g., the degree of engineering acceptance as expressed on a 1 to 5 scale). The lead design engineers covered not only the assessments made, but also the data used and specific technical bases for their judgments.

During or following the summary of each DF and DA by the lead design engineers, a performance assessment analyst described how the DFs and DAs were portrayed in the performance assessment analysis, the assumptions made, and the calculation results. The LADS team then evaluated the uncertainties associated with the modeling and degree of confidence in the representation of the DAs and DFs in the performance assessment. The calculated results, based on central estimates for the inputs (except for the waste package corrosion parameters,

Table 5-1. Summary of Design Feature and Design Alternative Evaluations
(License Application Design Selection Enhanced Design Alternative
Workshop-January 4, 1999)

Design Feature or Design Alternative	Postclosure Performance					Preclosure Performance		Assurance of Safety		Engineering Acceptance		Construction, Operations, and Maintenance		Schedule (relative to Viability Assessment)		Cost (total cost relative to Viability Assessment)		
	Assessment			Confid. —lead design engineer	Confid. — Performance Assessment	Assessment	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment + higher -lower	Confid.	
	10,000 yr. dose (mrem/yr)	Peak dose (mrem/yr)	Timing Figure of Merit															
Design Features																		
DF 1 – Ceramic Coatings	0.042	301 @317ky	25	D	E	2.6	B	2.0	B	3 (2.875-3.125)	D	2.6	B	Increase license & design	C	+ \$733M w/backfill \$373M	D	
DF 2 – Drip Shields	<0.01	<100		D	B	3	NA	4.5	C	4.8	A	3.25	A	Viability Assessment	A	\$2.2B mailbox	B	
DF 3 – Backfill	<0.001	[same as Viability Assessment]	[same as Viability Assessment]	D+	B	3	NA	3.33	C	4	B	3	B	Viability Assessment + 3yr	B	+ \$330 to \$350M	B	
DF 4 – Aging and Blending of Waste Blending	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	A	C+													
						3	C	3	A	2.75	B	3	D	Viability Assessment + 1yr	D	\$8M	NAV	
Aging						2.8	B	3	A	2.88	B	3.25	D	NAV	D	\$1.37B	NAV	
DF 7 – Continuous Preclosure Ventilation	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	D	C	3.25	A	3	B	3	A	3.06	B	Viability Assessment	B	+\$243-1,864M	A	
DF 8 – Rod Consolidation	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	C	B	1.6	B	2.0	B	2.6	B	1.5	B	Viability Assessment	D	+\$600M to -600M	C	
DF 9 – Timing of Repository Closure (100yr)	NA	NA	NA	NA	NA	2		NA	D	2.5	C	2.75	C	Viability Assessment	C	+\$3,871M	C	
DF 10 – Maintenance of Underground Features and Ground Support (300yr)	NA	NA	NA	NA	NA	2.5	C	NA	NA	2.83	B	3	B+	Viability Assessment	A	+\$9,289M	A	
DF 11 – Drift Diameter	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	NAV														
> 5.5 m						C	2.75	B	2.5	B	2.86	B	3	A	Viability Assessment	C	+\$181M	C
< 5.5 m						D	3.25	B	3.5	B	3.13	B	2.75	A	Viability Assessment -1.8yr	C	-\$236M	C
DF 12 – Drift Spacing/Waste Package Spacing (line load)	0.20355	284	26	E	B	3	C	3.5	C	3.57	C	3	B	Viability Assessment	B	-\$837M	B	
DF 13 – Waste Package Self Shielding Magnetite Concrete	NA	NA	NA	NA	NA													
Ducrete®						3.2	C+	2.67	D+	3.25	C+	2.25	C+	increase	D+	\$12B	NAV	
						3.4	C+	NAV	NAV	2.88	C+	3	C+	Viability Assessment	D+	NAV	NAV	
DF 14 – Waste Package Corrosion Resistant Materials (Titanium Alloy Grade 7 [Ti-7] and Alloy-22	0.014 @ 5.6ky	78 @ 717ky	3	B	D	3	A	3.7	B	3.1	A	3	A	Viability Assessment	B	+2.6B (Ti-7/ Alloy-22) +400M (ceramic) +150M (Alloy-22/ A516)	B	
DF 15 – Richards Barrier	<0.001	[same as Viability Assessment]	NAV	D	E	3	NAV	4	C	4	B	2	B	Viability Assessment +6yr	C	+\$600M	C	
DF16 – Diffusive Barrier under the Waste Package	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	C	D	3	A	3	C	2	C	2	A	Viability Assessment	B	NAV	B	
DF 17 – Getter under the Waste Package																		

Table 5-1. Summary of Design Feature and Design Alternative Evaluations
(License Application Design Selection Enhanced Design Alternative
Workshop-January 4, 1999) (Continued)

Design Feature or Design Alternative	Postclosure Performance					Preclosure Performance		Assurance of Safety		Engineering Acceptance		Construction, Operations, and Maintenance		Schedule (relative to Viability Assessment)		Cost (total cost relative to Viability Assessment)	
	Assessment	Confid.	Confid.	Confid.	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment + higher -lower	Confid.
Design Features	10,000 yr. dose (mrem/yr)	Peak dose (mrem/yr)	Timing Figure of Merit	Confid. —lead design engineer	Confid. —Performance Assessment	Assessment	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment + higher -lower	Confid.
1.2 m thick	0.04	214 @ 317ky	16	D	D	3	A	3	D	3	C	2	A	Viability Assessment	B	+\$846M	B
0.3 m thick	0.042	424 @ 317ky	24	D	D	3	A	3	D	3	C	2	A	Viability Assessment	B	\$155M	B
DF 18 – Canistered Assemblies (all fuel assemblies)	0.012	259 @ 317ky	22	C	B	5	C	3.3	B	3.1	B	NAV	E	Viability Assessment	A	+\$1.0B (all fuel) \$70M (stainless clad only)	D
DF 19 – Additives and Fillers: Integral Filler	0.40	301 @ 317ky	25	D	C	3	A	4	A	5	A	3	A	NAV	NAV	+\$131M	NAV
Iron oxide or partial shot	0.04	252 @ 317ky	18		C	3.2	A	4	A	5	A	2.5	A	NAV	NAV	+\$23M	NAV
Complete shot	0.04	265 @ 717ky	15		D	3	A	4	A	5	A	3	A	NAV	NAV	+\$98M	NAV
DF 20 – Ground Support Options																	
Unlined/Rock bolts	0.14	181	33	D	NAV	3	C	2	C	3+	C+	3	B	Viability Assessment	A	+\$1M	A
Steel sets	0.14	181	33	D	B	3	A	4	B	4	C+	3	B	Viability Assessment	A	-\$93 to +\$851M*	A
Concrete	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	D	D	3	A	3	D	3	C+	3	B	Viability Assessment	A	0	NAV
DF 22 – NF Rock Treatment during Construction	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	D	C	3	B	4	B	2.57	B	3	B	Viability Assessment	D	+\$500M	D
DF 23 – Surface Modifications																	
Alluvium Added	<1e-10	338	25	C	C	3	A	2	C	3.3	B	2.8	A	Viability Assessment*	NAV	+\$3.1B	B
Alluvium Removed	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	C	B	3	A	2	A	3.3	D	2.8	A	Viability Assessment	NAV	+\$138M	B
DF 25 – Repository Horizon Elevation																	
+ 50meters	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	B	NAV	3.5	B	NAV	B	3.67	C	2.83	B	Viability Assessment	B	+\$160M	B
Full size two-tier	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	D	NAV	3.25	B	NAV	C	3.78	C	2.67	B	Viability Assessment	C	+\$7.3M	B
Half-size two-tier	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	D	NAV	3.25	B	NAV	C	3.78	C	3.17	B	Viability Assessment	C	+\$1.4M	B
DF 26 – Higher Thermal Loading	0.32	NAV	44	NAV	C	3.25		3.5	C	3	C	2.75	B	Viability Assessment (less)	C	-\$500M	C
Design Alternatives																	
DA 1 – Tailored Waste Package Spatial Distribution	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	B	NAV	2.2	C+	1.33	C+	2.875	B	2.25	B+	Viability Assessment	E	NAV	D
DA 2 – Low Thermal Load Design (25 MTHM/acre)	0.003	130	NAV	C+	E	3	C	5	A	4	B+	3	B	>Viability Assessment	C	+\$4B	D

Table 5-1. Summary of Design Feature and Design Alternative Evaluations
(License Application Design Selection Enhanced Design Alternative
Workshop-January 4, 1999) (Continued)

Design Feature or Design Alternative	Postclosure Performance					Preclosure Performance		Assurance of Safety		Engineering Acceptance		Construction, Operations, and Maintenance		Schedule (relative to Viability Assessment)		Cost (total cost relative to Viability Assessment)	
	Assessment			Confid. —lead design engineer	Confid. — Performance Assessment	Assessment	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment	Confid.	Assessment + higher -lower	Confid.
Design Alternatives	10,000 yr. dose (mrem/yr)	Peak dose (mrem/yr)	Timing Figure of Merit														
DA 3 – Continuous Postclosure Ventilation Design	NAV	NAV	NAV	C	E												
Closed-loop						3	A	2	C	2.625	A	2.8	B	Viability Assessment	C	+\$575M	B
Open-loop						3	A	2	C	2.75	C+	2.8	B	Viability Assessment	C	+\$244M	B
Closed/open-loop						3	A	2	C	2.375	C	3	B	>Viability Assessment	C	NAV	NAV
DA 4 – Enhanced Access Design	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	NAV	NAV												
Integral Shield						3.2	B	3.3	B+	3.5	B	2.5	B	Viability Assessment	B	→ \$600M	D
Supplemental Shield						3	C+	3	B	3	C	2.5	B	Viability Assessment	B	→ \$300M	B
Shielded Cart						3	B	3	A	3	C	2.675	B	Viability Assessment	B	-\$250M	E
DA 5 – Modified Waste Emplacement Mode Design																	
Short cross-drifts	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	B	NAV	2.8	C	3	C	3	C	3	B	Viability Assessment	D	+\$1.8B	E
Vertical boreholes	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	C	NAV	2.2	C	2.5	C	2.8	C	2.8	B	Viability Assessment	D	+\$6B-\$7.4B	E
Concrete or marble trench	[same as Viability Assessment]	[same as Viability Assessment]	[same as Viability Assessment]	D	NAV	2.6	C	2.5	C	3	C	3	B	Viability Assessment	D	+\$975M	E
DA 6 – Viability Assessment Design	0.042	300 @ 317ky	25	NAV	D	3	B	3	B	3	D	3	C	Viability Assessment	****B to D+	0	A
DA 7 – Viability Assessment Design w/Options	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV
NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	NAV	

- * \$93M less for steel sets and wire mesh; \$486M more for steel sets and panel lagging; \$851M more for steel sets and steel channel lagging
- ** If liner fails and serves as lower backfill; much higher (as much as two orders) if liner stays up and conditions water
- *** Construction estimated to take 25 years, but would occur during emplacement, so no impact on schedule
- **** Moderately low confidence for design stage; moderately high confidence for emplacement stage
- NA: Not applicable; NAV: Not available

which were sampled), were compared with the Viability Assessment design. Under questioning from the LADS team, the performance assessment analysts provided their judgments regarding the significance of the calculated results; that is, whether a calculated result differed significantly (higher or lower) from the Viability Assessment design.

The lead design engineer presentations provided the LADS team an opportunity to understand how each design was defined and, most important, the technical basis for the way each design was evaluated against the evaluation criteria. Listening to the lead design engineers enabled the LADS team to review the evaluations across the entire collection of DFs and DAs.

Toward the end of the first general session, presentations were given on the Viability Assessment performance confirmation program and postclosure defense in depth. The presentation on the performance confirmation program focused on the program approach, strategy, and major performance confirmation elements. The presentation on defense in depth focused on the concept of assuring safety by using multiple redundant barriers. A procedure for identifying and evaluating principal design barriers and then neutralizing them to evaluate the overall system defense in depth was discussed. The goal was to help design team members understand defense in depth and consider the concept when developing candidate EDAs. A preliminary evaluation of defense in depth was carried out as part of Phase II.

5.1.2.2 Division into Working Breakout Teams

To facilitate development of a range of diverse EDAs, the participants in the workshop were divided into three working breakout teams focused on three broad classes of designs: high-temperature designs, low-temperature designs, and designs allowing enhanced human access. This division reflected two major dimensions in which the Viability Assessment design could be changed: 1) the temperatures in the repository caused by the heat emitted by the radioactive waste, and 2) the ease of human access to the drifts containing the waste that has been emplaced in the repository.

Temperatures in the Repository—A U.S. Nuclear Regulatory Commission staff report (NRC 1992, p. 10) states that “it is likely that repository-induced thermal loading of the host rock, surrounding strata, and groundwater system may be one of the most important underground design parameters for the [geologic repository operations area] GROA.” The more waste in each waste package, and the larger the quantity of waste per acre of underground repository space, the higher the temperatures will be in and around the waste packages and in the surrounding rock. The Viability Assessment design uses large waste packages (21 pressurized-water reactor [PWR] assemblies or 44 boiling-water reactor assemblies) with heat output as high as 18,000 watts, and an emplacement density of 85 metric tons of heavy metal (MTHM) of waste per acre. This could lead to postclosure temperatures above the boiling point of water on the surface of the waste package and in the rock throughout the entire repository. Reducing the thermal load to lower the waste package surface temperature and keep temperatures in much or all of the repository rock below the boiling point of water would improve the predictability of performance and reduce uncertainties resulting from changes in the repository environment caused by the heat from the waste. On the other hand, although the predictability of the seepage might be improved, the use of heat to dry the rock around the emplacement drifts for an extended period, thus reducing or

eliminating seepage, may have benefits in actual performance. The ability to predict the performance is a key driver for successful licensing.

Enhanced Human Access—In the Viability Assessment design, all activities in the emplacement drifts must be conducted remotely when waste packages are present. The radiation emitted by the packages would be too high to allow human access without additional shielding, and there were no provisions for such shielding. Waste packages must be removed from the drift, and forced ventilation used to reduce the temperature in the drift, before humans could enter for any purpose. In one approach, all of the needed operations in the drift with waste present could and should be performed using remote equipment. Alternatively, provisions for human access to drifts containing waste could be required in at least some situations, such as unexpected events that might require human inspection to determine what measures need to be taken.

Summary—The Viability Assessment design represents a high-temperature design that does not allow direct human access to the loaded drifts. The creation of working breakout teams, focused on designs that differed significantly from the Viability Assessment design in these two important dimensions, was intended to ensure that the resulting set of alternatives would reflect the significant differences in philosophy on the thermal and human access issues, and would therefore represent more than minor variations on the Viability Assessment design. In developing alternatives, both the high- and low-temperature groups were allowed to consider enhanced access options if they so chose, while the enhanced access group was allowed to consider both high- and low-temperature options.

5.1.2.3 First Pass by Enhanced Design Alternative Teams (Breakout Session on Day 4)

The three EDA teams consisted of representatives from the larger LADS team. Team members were selected to include a representative from each operations area. This ensured that all teams had enough expertise to develop candidate designs, as well as access to the resources of all Management and Operating Contractor operations areas to support their deliberations. The lead design engineers served as resources for all of the teams, so that any questions regarding specific data about DAs or DFs could be addressed during the team discussions. Each team included a lead responsible for presenting the results of the breakout sessions, along with a facilitator and a recorder. Representatives from the DOE, the Nuclear Waste Technical Review Board, and other organizations observed the breakout sessions, participated in the discussions, and provided valuable input.

To ensure diversity of the designs, each team focused on a different alternative design concept and developed candidate EDAs based on that concept. The teams worked to build the best candidate designs with the highest levels of confidence relative to the evaluation criteria. They focused on the following basic design concepts:

- Low-temperature designs
- Enhanced access designs
- High-temperature designs

These three design concepts are not mutually exclusive, but having each one as a focus of principal concern meant that diversity could be ensured and areas of overlap could easily be

identified. The three concepts spanned the range of DAs considered in Phase I. In this exercise, DA 1 (Tailored Waste Package Spatial Distribution) and DA 8 (Modular Design/Phased Construction) were treated like DFs in the sense that they could be part of any candidate EDAs developed by any team.

To assist the three EDA teams in their deliberations, guidance on the purpose of the activities and the overall system goals was provided in the general workshop session at the end of Day 3. The guidance included the following:

- Since all EDAs were to be evaluated against the EDA evaluation criteria, candidate EDAs should be built up using these criteria (preliminary performance assessment, defense in depth, and cost evaluations were made during the workshop to help with this process).
- All candidate EDAs should strive for simplicity in design such that the system elements and functions are clear, readily communicated, and defensible.
- All candidate EDAs should address the four attributes of the repository safety strategy; if they do not address all four, it must be shown that accommodation of the elements addressed mitigates the need to address all four elements.
- Designs should incorporate multiple, diverse barriers to enhance defense in depth.
- Confidence in design postclosure performance, preclosure performance, assurance of safety, and other evaluation criteria is important, and the level of confidence should be considered in developing candidate EDAs.
- EDA teams were not constrained to using only the base DAs, but could use DAs assigned to another team if appropriate.

The first-pass breakout session was the first opportunity for the LADS team members to consider combinations of DAs and DFs in the context of the principal area of focus of each team. Brainstorming and creativity were encouraged. Rather than following a rigid structure, a flexible process was used in each breakout session. This approach took the teams from defining their area of focus, to considering DAs and DFs that would enhance their designs, to developing candidate conceptual designs for discussion at the general session the next day. The procedural steps are described below; detailed information on the deliberations of each team is provided in Section 5.1.3. The degree of emphasis on each step varied among the teams. All teams addressed the first step; the second step received less emphasis from the low-temperature and enhanced access teams; and all teams addressed the third step, with the enhanced access team making a preliminary consideration of the evaluation criteria.

Step 1: Define the focus of the breakout session. Each team was provided with a broad design characteristic as its principal focus for consideration: high-temperature, low-temperature, or enhanced access designs. The first step was for each team to define what that characteristic meant. For example, the low-temperature design team defined their topic as follows: First, a distinction was made between low temperatures associated with the influence of a single waste package (in either a point-loading or line-loading configuration) and a “low thermal loading”

design that considered spatial average thermal loading across the entire repository. The team's low-temperature designs emphasized the first concept. Then four temperature states were defined at certain locations (at two locations within the rock surrounding the drifts, at the drift wall, and on the waste package). These elements of the definition were then used as goals in the consideration of DFs and DAs.

Step 2: Consider the relevance of various DFs and DAs and their interactions to the team focus. After each team defined its principal focus, it identified the DFs and DAs relevant to that focus. The low-temperature design team identified features such as aging and blending, preclosure ventilation, waste package size and heat output, backfill, and fillers as relevant to low-temperature designs. The high-temperature team at first considered every DF as an enhancement to the Viability Assessment design. After analyzing the features during LADS Phase I evaluations, the team identified positive and negative interactions. As an example, surface aging of the waste was seen as possibly lowering temperatures after emplacement, while backfill might raise waste package surface temperatures following closure. However, backfill might extend the life of a drip shield by protecting it from rockfall. In most cases, little time was spent on this step because team members were familiar with the interactions among the DFs and DAs.

Step 3: Identify candidate EDAs. Candidate design concepts were constructed from the design concept definitions and the pros and cons of the various DFs and DAs. Each team concentrated on the design elements that would address the focus of their team, while remaining conscious of the evaluation criteria against which the designs would ultimately be evaluated. The teams kept their assessments qualitative. The teams were not limited to selecting only designs expected to score well against each evaluation criterion or to optimizing the designs against all of the criteria. This type of evaluation would come later, in Phase II. In many cases, data and information developed for the DAs and DFs (or as part of other studies for the Yucca Mountain Site Characterization Project) were used in developing the candidate designs. For example, the low-temperature team drew on project-developed data and analyses related to waste package surface temperatures associated with various areal mass loadings, waste package heat outputs, and aging; the high-temperature team employed data from the Phase I analysis of alternative waste package materials and closed-loop circulation systems.

First-Pass Summary: Candidate Designs (General Session on Day 5)—After their first-pass evaluations, participants reconvened in a general session of the workshop. Each team representative presented the candidate designs the team had identified, describing the components of the designs and the rationale for including them in the candidate EDAs. Workshop participants were cautioned to refrain from debating the merits and demerits of the three basic design concepts, but to focus on the candidate EDAs. The low-temperature team representative described the team's thermal goals for low-temperature designs and identified design elements that could accomplish them, presenting eight different low-temperature design concepts. The high-temperature team representative presented 11 design concepts, three of which contained enhancements to the Viability Assessment design. The presentation from the enhanced access team began with a discussion of the criteria for access, which the team defined as repository access only for "off-normal events," not for operational or continuous access. The team representative described four design concepts and assessed them with respect to the evaluation criteria.

At this facilitated general session, the teams were encouraged to question and challenge the assertions of other teams and to support their own interpretations. This interchange clarified the technical bases for the candidate designs and the basis for the confidence assessments. The goal was to provide feedback to the teams to help them modify and refine their designs in the second pass.

The DAs and DFs that were not included in any of the candidate EDAs were also discussed. Some were not included because they were judged to not clearly improve performance (e.g., DF 22, near field rock treatment during construction) or were subject to considerable uncertainties in operability or effectiveness over time (e.g., DF 23, surface modification, remove alluvium option). Other DAs and DFs were judged potentially useful for several design options, but were held aside as possible enhancements to the fundamental concepts that might be added later.

5.1.2.4 Second Pass by Enhanced Design Alternative Teams: Refinement and Reduction of Candidate Enhanced Design Alternatives (Breakout Session on Day 6, Morning)

Using the feedback provided in the first general session, each EDA team was instructed to review, refine, and reduce the set of candidate EDAs developed in its first pass. The teams used information from the operations areas in their deliberations. For example, the high-temperature team discussed specific design concepts and their hydrological implications on multi-level designs with staff from the Natural Environment Operations Area. The low-temperature team commissioned thermal-hydrology calculations to examine the relationships between areal mass loading, drift spacing, aging, waste package heat output, and temperatures on the waste package surface, the drift wall, and across the pillars between drifts. The enhanced access team considered calculations of waste package surface radiation doses—both total doses and gamma/neutron components—associated with various waste package shields and thicknesses. These deliberations served to better focus the design concepts, discard those that were not appropriate or were redundant with other designs, and reduce the number of candidate EDAs.

Second-Pass Summary: Short List of Candidate EDAs (General Session on Day 6, Afternoon)—Following their evaluations in the second pass, the teams met again in a facilitated general session. The teams presented their candidate EDAs and discussed how these would meet the proposed Phase II evaluation criteria and other guidance. The low- and high-temperature design teams had combined or eliminated design concepts to come up with three and six candidate EDAs, respectively. The enhanced access team carried forward the four candidate EDAs developed in the first pass, but identified key issues that needed clarification, such as shielding requirements. Once again, the teams were questioned regarding the basis for their assessments and the degree of confidence they placed in their evaluations.

The teams also discussed key issues needing clarification, either during the workshop or during the next few years. These included uncertainties about performance and how they might be represented in the future, questions about application of the defense-in-depth concept (e.g., how individual barriers were identified), and the potential for licensing specific DFs such as blending, cladding, and backfill.

5.1.2.5 Consideration of Performance Assessment, Defense in Depth, and Cost, and Refinement of Candidate Enhanced Design Alternatives (Breakout Sessions on Days 7 and 8)

Using the feedback from the general session, the teams reviewed the candidate EDAs in further detail. Each team met with representatives familiar with performance assessment models, defense in depth analysis, and cost estimation to obtain additional information on each candidate EDA. The performance assessment representatives described available and proposed models that could provide more accurate postclosure performance assessment. They answered questions on the importance of certain technical issues affecting design, such as the temperature thresholds at which certain waste package alloys initiate localized corrosion. Uncertainties in postclosure performance were also discussed, including the predictability of thermal-hydrologic processes and the difficulty associated with assessing the performance of different design concepts. The defense-in-depth representative focused on the ways various design components might be considered as independent barriers, identifying design functions and possible common failure modes. Basic components of the candidate EDAs were then reviewed with the cost estimation representatives to explore how different design components and concepts might be configured. Questions that could not be answered in the sessions were addressed later on in the two-day period by the representatives. These assessments provided additional information to the EDA teams to refine their candidate designs and, ultimately, assist the core team in the final selection of EDAs.

It became apparent while developing candidate EDAs that, given the large number of possible DFs and implementations from which to choose, it would be valuable to identify those design components that would be fundamental or integral to the design and those components that would be supportive of the concept, but not essential. Components might also be judged to be independent of the basic design concept, but useful for performance enhancement or defense in depth. To assist in the team's deliberations, a checklist was developed to record the DAs and DFs in each candidate EDA. The checklist was organized by features related to percolation flux, the waste package, the repository, the area inside the waste package, the engineered barrier system, and temperature/relative humidity management. Implementing features were organized in the following categories:

- Integral to the design
- Supportive but not integral
- Independent of the design
- Not selected

Characterizing design elements in this way highlighted the principal elements of each candidate EDA. The "independent" features were highlighted as relating primarily to defense in depth and performance enhancement. These features could be used in more than one EDA.

5.1.2.6 Selection of Enhanced Design Alternatives (General Session on Days 9 and 10)

The candidate EDAs developed by each design team were reviewed. The low-temperature, high-temperature, and enhanced access teams proposed two, four, and three candidate EDAs, respectively. A large table was constructed to show the implementing features of the nine

candidate EDAs (Table 5-2). The LADS core team agreed to eliminate one candidate EDA proposed by the high-temperature team from further consideration (High Temperature: A), which was similar to the Enhanced Access Waste Package (Viability Assessment with Options) design. In discussing the designs, the core team concluded that the two layouts were so similar, a separate candidate EDA was not needed.

The eight remaining candidate EDAs were discussed extensively, along with the possibility of incorporating elements of the enhanced access designs into the low- and high-temperature EDAs. The advantages and disadvantages were considered, but the group concluded that more explicit information was needed before the elements of enhanced access could be folded into the other designs. Aspects of the candidate EDAs were discussed, particularly the bow-tie postclosure ventilation system proposed as part of a high-temperature team candidate EDA. The group observed that there were uncertainties for such a ventilation system with respect to long-term operability and related licensing issues. Coupled near-field processes and the related uncertainties for mid- to high-temperature repository conditions were examined. Defense in depth, and DFs, such as drip shields and backfill, that could enhance defense in depth, were also discussed.

The LADS core team concluded that the eight candidate EDAs should all be considered for further analysis. The goal of the Phase I workshop to develop a diverse set of candidate EDAs was met with this decision.

5.1.3 Enhanced Design Alternatives Developed in Workshop

The EDA teams met in breakout sessions to develop design concepts and candidate EDAs. The goals for each design concept and the integral elements of the candidate EDAs are summarized in Table 5-2 and listed below. The core team recognized that specifying each integral element of the EDAs would require further engineering analysis to better refine the general design concepts. For example, the drift spacing, aging, and configuration needed to achieve a temperature goal would have to be adjusted following the workshop.

5.1.3.1 Low-Temperature Designs

The design goals were to:

- Make the predictability of thermally activated processes more defensible
- Create a more benign environment for waste packages
- Preserve natural barriers
- Facilitate access to waste packages

Alternative temperature objectives considered to obtain these goals were: 1) keep the near-field rock (normally within 10 m of the drift wall) below the normal boiling point at this elevation (~96°C, not considering chemical or capillary effects); 2) keep the drift wall below the normal boiling point; 3) keep the waste package surface below the normal boiling point of water; and 4) keep the waste package surface below 80°C. The first two temperature states would increase the repository system predictability; the second two would enhance the waste package lifetime.

Table 5-2. Candidate Enhanced Design Alternatives Worksheet
(License Application Design Selection Enhanced Design Alternative Workshop—January 15, 1999)

Candidate Enhanced Design Alternative	Low Temperature Line Load	Low Temperature Point Load	High Temperature: A	High Temperature: B	High Temperature: C	High Temperature: D	Enhanced Access: Waste Package (Viability Assessment w/options)	Enhanced Access: Waste Package + Emplacement Mode	Enhanced Access: Emplacement Mode
Areal Mass Loading	50 (Integral)	40 (Integral)	85 (Integral)	85 (Integral)	85 (170 Locally) (Integral)	150 (Integral)	85 (Supportive)	85 (Supportive)	85 (Supportive)
Waste Package Size (PWR)	12 (Integral)	21 (Integral)	32 (Independent)	32 (Independent)	40 (Supportive)	32 (Independent)	21 (Supportive)	21 (Supportive)	21 (Supportive)
Blending Maximum kw	5 (Integral)	14 (Integral)	18 (Supportive)	21 (Supportive)	27 (Supportive)	21 (Supportive)	18 (Independent)	18 (Supportive)	5 (Integral)
Area (acres)	1300 (Integral)	1600 (Integral)	800 (Integral)	800 (Integral)	800 (Integral)	450 (Integral)	800 (Supportive)	800 (Supportive)	800 (Supportive)
Drift Diameter (meters)	4.5 (Integral)	5.5 (Integral)	5.5 (Integral)	5.5 (Integral)	5.5 (Integral)	5.5 (Integral)	5.5 (Supportive)	5.5 (Supportive)	5.5 RH (Integral)
Drift Spacing (meters)	45 (Integral)	60 (Integral)	28 (Integral)	56 (Integral)	28 (Integral)	30 (Integral)	28 (Supportive)	28 (Independent)	56 (Supportive)
Waste Package Material	CRM/outside (Integral)	CRM/outside (Integral)	Alloy-22/Ti-7 (Independent)	Alloy-22/Ti-7 (Independent)	Alloy-22/Ti-7 (Independent)	Alloy-22/Ti-7 (Independent)	SS/Alloy-22 (Supportive)	A516 30cm (Integral)	Alloy-22/Ti-7 Steel (Supportive)
Avg Heat After BI & Aging	2 (Integral)	4 (Integral)	14 (Independent)	14 (Independent)	18 (Supportive)	14 (Supportive)	9 (Independent)	9 (Supportive)	5 (Integral)
Aging (years)	50 (Integral)	50-100 (Integral)							50-100 (Integral)
Preclosure Ventilation	Y (Integral)	Y (Integral)		Limited (Integral)	Y (Integral)	Y (Integral)			
Postclosure Ventilation	(Not Selected)	(Not Selected)			Y (Integral)		(Not Selected)	(Not Selected)	
Rod Consolidation					At Utility (Supportive)				
Layout	Viability Assessment (Integral)	Viability Assessment (Integral)	Viability Assessment (Integral)	Viability Assessment (Integral)	Bow-tie (Integral)	Viability Assessment (Integral)	Viability Assessment (Integral)	Short Cross-Drift (Integral)	Viability Assessment (Integral)
WP Ceramic							Y (Supportive)		
Drip Shield				Ceramic (Independent)		Ceramic 10% (Supportive)	Y (Independent)	Y (Independent)	Y Marble (Integral)
Canistered Assemblies							BA (Supportive)	BA (Supportive)	BA (Supportive)
Backfill				Y (Independent)			Y (Independent)	Y (Integral)	Y (Integral)
Liner Invert			Concrete (Independent)	Concrete (Independent)	Concrete (Independent)	Concrete (Independent)		Steel (Supportive)	Rock bolts Mesh (Independent)
Filler					(Not Selected)			Integ. filler (Supportive)	
Trench					(Not Selected)				Marble (Integral)
Shielding					Navy Size DHLW Thick Steel (Supportive)		Perm-γ Temp-n (Supportive)	Perm-γ Temp-n (Supportive)	Temp-γ Temp-n (Supportive)

BA: Only damaged or SS clad fuel
Alloy-22: nickel-based alloy
Ti-7: Titanium alloy grade 7
A516: Carbon steel
RH: Roadhead excavation

perm gamma: Permanent shielding for gamma radiation
temp n: Temporary shielding for neutron radiation
Viability Assessment: Comparable to Viability Assessment design
CRM: Corrosion-resistant material
DHLW: Defense high-level radioactive waste

Based on considerations of performance, cost, and achievability, Objectives 1 and 2 were judged to represent very similar conditions and Objective 4 was not achievable without major design implications (e.g., very small waste packages). As a result, Objectives 2 and 3 were adopted. The team decided these objectives achieved most of the design goals and provided EDAs that would be likely to succeed.

Two candidate EDAs were carried forward at the end of the workshop. The first was based on line loading at 50 MTHM/acre and the second on point loading at 40 MTHM/acre. The line-loading concept, which would require 1,260 acres of the characterized area, would achieve a more uniform and predictable temperature profile along the drifts. The spent nuclear fuel would be aged up to 50 years on the surface of the repository or elsewhere and blended to produce a targeted waste package heat output within 20 percent of the average PWR waste package. The waste package would consist of a corrosion-resistant material over a structural inner material (e.g., carbon or stainless steel), and would be large enough to accommodate 12 PWR spent nuclear fuel assemblies. The drift diameter would be 4.5 m for improved stability, and the drift spacing would be 45 m.

In the point-loading concept, 1,570 acres of the potential characterized area would be needed to meet the 40 MTHM/acre areal mass loading requirement. The spent nuclear fuel would be aged 50 to 100 years and blended to produce maximum thermal outputs within 20 percent of the average. The waste package would have a corrosion-resistant outer layer over a structural layer and would accommodate 21 PWR assemblies. The drift diameter would be 5.5 m, and the drift spacing would be 60 m.

5.1.3.2 High-Temperature Designs

The design goals were to:

- Drive water away from the engineered barrier system and waste package for as long as practicable (water must be shed, removed in ventilation, or imbibed in the rock matrix)
- Avoid extended periods of warm, moist conditions (i.e., temperatures at the waste package should be kept lower than 80°C or higher than 100°C and the relative humidity less than 90 percent)
- Maintain long-term performance even if one or two barriers are compromised
- Have sufficient space in the primary area to contain all U.S. waste, if additional emplacement capacity is authorized
- Limit cost

The design approaches developed to address these goals were to:

- Limit drift wall temperature to 225°C to limit ground support loads
- Remove water from the system

- Thermally divert seepage of new percolation flux while waste packages are hot
- Limit internal waste package temperature to lower than the cladding limit of 350°C for extended periods
- Allow zeolites to exceed 90°C for no more than another 100 m of depth (to 270 m below the repository horizon); would not change the minimum thickness of preserved zeolites across the repository footprint

Three candidate EDAs were carried forward from the workshop. The major differences between two of the three were areal mass loading, repository area, number of drifts and waste packages, drift spacing, and waste package capacity. The 85 MTHM/acre line-load candidate EDA would require a 740-acre repository area, 40 drifts and 8,170 waste packages, drift spacing of 70 m, and 32 PWR waste packages. The 150 MTHM/acre line-load candidate EDA would require a 400-acre repository area, 40 drifts and 8,170 waste packages, 40 m between drifts, and 32 PWR waste packages. The third candidate EDA was a fundamentally different concept incorporating postclosure ventilation using a bow-tie repository layout. It required 170 MTHM/acre, a 400-acre area for waste packages within an 800-acre repository footprint, 66 drifts and 6,740 waste packages, drift spacing of 42 m, and 42 PWR assemblies consolidated into waste packages with diameters similar to the 21 PWR waste package in the Viability Assessment design.

5.1.3.3 Enhanced Access Designs

The design goals were to:

- Provide a means to empty drifts without human access
- Make provisions to handle major expected events using remote equipment
- Provide for human access, on a campaign basis, in unanticipated (off-normal) events

Three candidate EDAs were carried forward from the workshop: 1) waste package providing access; 2) waste package and emplacement mode provide access; and 3) emplacement mode providing access. The first concept was based on using a portable neutron shield to reduce the neutron dose for off-normal events and a waste package with a thick, stainless steel outer barrier (stainless steel 316L) to provide gamma shielding. The second concept included a repository layout with a short cross-drift between Viability Assessment-design type drifts. The short cross-drifts could be cooled more effectively and would limit the number of waste packages in a single drift, allowing for easier retrieval. A "mailbox" temporary neutron shield would be used for access, if necessary. The waste package would consist of a single layer of carbon steel (A516) with an integral filler; damaged fuel rods would be placed in canisters. The third concept would include trench emplacement in a marble trench liner for water chemistry control, with a marble top installed at closure to act as a drip shield. The trench would be installed in a noncircular drift (tunnel boring machine-excavated drift with modifications to widen the inverts). Temporary concrete shielding could be placed on the open trench top to provide access. The operations concept would be to emplace only low-temperature output waste packages (4 to 5 kW maximum, aged and blended to achieve this limit), constructing drifts and fabricating waste packages as needed ("just in time"). Performance confirmation drifts could be minimized, because confirmation could begin as soon as the waste packages were emplaced.

5.1.4 Selection of Enhanced Design Alternatives for Phase II

Following completion of the EDA workshop, the eight candidate EDAs developed at the workshop were reviewed and refined by the LADS core team to arrive at the EDAs to be analyzed in Phase II. As part of this refinement, the core team considered a number of potentially significant issues that might serve to further constrain the design concepts:

- Keeping the temperature of the spent fuel cladding below 350°C to avoid possible breach of the cladding by creep rupture. The pinholes from such breaches could allow water to contact the fuel pellets after the waste packages are breached. If the waste package is also breached during the thermal pulse (in this case while spent nuclear fuel temperatures are above about 200°C), pinholes and cladding can result in more extensive clad failure due to expansion of waste as it oxidizes.
- Being able to close the repository (beginning 50 years after the start of emplacement)
- Maintaining thermal independence of the emplacement drifts (defined as not allowing the boiling fronts between drifts to coalesce)
- Allowing personnel access (defined as the ability to gain access to the emplacement drifts in response to off-normal events)

In addressing these issues, the following approaches were used:

- Personnel access was addressed by imposing a requirement. Recognizing there are uncertainties in assessing adherence to a requirement, management should be alerted if a requirement is to be exceeded.
- Other issues are resolved by attempting to stay within limits unless there are clear benefits to not doing so. Management should be informed before such a limit is exceeded. Examples of issues in this category are the 350°C cladding temperature limit and closure at 50 years.
- Other issues are resolved by considering limits for the design. An example of an issue for this category is thermal independence of drifts.

The issue of personnel access requirements was outlined in greater detail, as follows.

5.1.4.1 Criteria and Guidance for Repository Enhanced Access Design

These criteria applied to all EDA designs:

- Personnel access provisions were to be included in the EDA to provide a capability to respond to operational off-normal and design basis events.^{4,5} These were defined as:
 - Waste package handling, support, or related problems
 - Waste package transporter malfunction
 - Utility malfunction (rail, power, lighting)
 - Minor ground-support problems, defined as localized degradation or failure of concrete, steel sets, mesh, and rock bolts, and including mechanical problems and water leakage
 - Backfill and drip shield emplacement systems and equipment problems
- If a need for access to emplacement drifts is established, it must be feasible within four calendar weeks.
- The access environment for personnel shall not exceed the following:
 - Combined neutron/gamma radiation exposure levels to personnel must be limited to 30 mrem/hr at the shield surface by using a combination of waste package materials, shielding, including portable, temporary shielding, based on an exposure of 40-hour maximum duration per quarter and 100-hour maximum duration per year.
 - Temperatures must not exceed 50°C.
- Access provisions may or may not include removal or movement of waste packages.

5.1.4.2 Final Enhanced Design Alternative Definition

Given these considerations and the Phase II evaluation criteria (See Section 5.2), the core team reconsidered the eight candidate EDAs. With refined requirements, it was decided personnel access could be part of any of the EDAs and could be accomplished principally through the use of portable equipment. Although the equipment was not quantified, a thickness of portable shielding required for each of the EDA designs was calculated and considered in the evaluation of the EDA. Also, waste packages could be removed or rearranged to allow access. A combination of waste package shielding and rearrangement provided flexibility to all of these designs. Preliminary calculations of waste package surface doses indicate that the requirements could be met with modest waste package self-shielding. Thus, more significant design

⁴ Major failures (e.g., gross failure of waste packages or ground support, such as drift collapse), whether or not induced by disruptive events, were not intended to be addressed as operational off-normal conditions and would be handled on a special campaign basis.

⁵ The preceding criteria do not apply to retrieval conditions.

considerations (e.g., trench emplacement or very thick waste package walls) were not required. This allowed the team to consider eliminating some elements of the enhanced access designs whose function was primarily for shielding.

The most effective way to ensure diversity in the final set of EDAs was to span a range of temperature goals, mindful of the constraints, goals, and considerations discussed above. A series of such goals was established dealing with temperatures at the waste package surface, drift wall, and centerline between drifts. Using the analyses developed during Phase I and the workshop, designs were then developed to achieve these goals, though it was recognized that additional engineering analyses would be needed to further refine the designs and verify that the goals would be met. Using this approach, a series of five EDAs, containing elements from the eight candidate EDAs, were developed. The temperature goals and EDAs are summarized in Table 5-3.

5.1.5 Standard Features and Design Rationale for Enhanced Design Alternatives

So that all of the EDAs to be analyzed in Phase II were on an essentially equivalent basis, an attempt was made wherever possible to use standard features among the designs. For example, the analyses used the waste stream assumptions from the Viability Assessment, including emplacement of 63,000 MTHM of commercial spent nuclear fuel and a total of 7,000 MTHM-equivalent of DOE spent nuclear fuel and high-level radioactive waste. Other standard features and their underlying rationale are described below.

5.1.5.1 Defense in Depth

DFs/DAs judged to have potential for possible defense-in-depth benefits were identified after the consideration of such issues as design compatibility, operability, licensability, performance uncertainties, and cost. These DFs/DAs are listed below. This list represents a menu from which to select additional enhancements, depending on the degree of defense in depth desired.

- Ceramic coating on waste package
- Drip shield (metal, monolithic ceramic, or ceramic-coated metal)
- Backfill (calcite, quartz, or tuff)
- Filler inside the waste package
- Dual corrosion-resistant materials waste package
- Richards Barrier
- Canistered assemblies
- Trench with lid

The analysis of the Viability Assessment design indicated that additional defense-in-depth features may be needed to address uncertainties in the engineered and natural barrier systems. There is insufficient defense in depth when the waste package is neutralized, which is mitigated by adding a drip shield (CRWMS M&O 1999mm, p. 13). Analysis of the DAs/DFs in Phase I of the LADS effort identified drip shields over the waste packages as a particularly promising way to enhance defense in depth. Drip shields are a potential barrier that may limit water contacting waste packages, which prolongs waste package life (CRWMS M&O 1999nn, p. 7). To simplify

Table 5-3. License Application Design Selection Enhanced Design Alternatives Identified at the End of Phase I (February 4, 1999)

Design Element ¹	EDA I	EDA II	EDA III	EDA IV	EDA V
Areal Mass Loading (MTHM/acre)	50	64	85	85	150
Area (acres) for 70,000 MTHM	1,260	980	740	740	420
Line/Point Load	Line or Point	Line	Line	Line	Line
Waste Package Size (PWR)	12	21	21	21	21
Rod Consolidation	No	No	No	No	Yes (42)
Drift Diameter (m)	4.5 (or 5.5)	5.5	5.5	5.5	5.5
Drift Spacing (m)	45	74	56	56	55.5
Aging/Preclosure Ventilation	25 / 25 years	25 / 25 years	0 / 50 years	0 / 50 years	25 / 25 years
After Aging and Blending: Maximum, Average ²	3.8 kW 3.2 kW	6.8 kW 5.7 kW	Limited blending 18 kW, 9.8 kW w/no aging	Limited blending 18 kW, 8.8 kW w/no aging	17.0 kW 11.4 kW
Waste Package Material	Inside out Viability Assessment	Inside out Viability Assessment	Inside out Viability Assessment and A-22/Ti-7	30 cm A516	Inside out Viability Assessment
Fillers				Integral filler	
Backfill	No	Yes	No	Yes	No
Drip Shield (2-cm-thick Ti-7)	Yes	Yes	Yes	Yes	Yes
Commercial Spent Nuclear Fuel Waste Package/Total Waste Packages	13,294 / 16,782	7,426 / 10,284	7,590 / 10,448	7,590 / 10,448	3,704 / 6,562

¹The goals below are the controlling basis for EDAs I through V. The design parameters could evolve during the EDA evaluation.

EDA I Goal: Drift wall less than 96°C, waste package less than 110°C, cladding less than 350°C.

EDA II Goal: Permit shedding between drifts at all times, cladding less than 350°C.

EDA III Goal: Drift wall less than 200°C, (some dryout in pillars), cladding less than 350°C, waste package surface cools down to less than 80°C before relative humidity gets back to 90 percent.

EDA IV Goal: Cladding less than 350°C, dryout in pillars, keep drifts dry for thousands of years, reduce gamma dose at waste package to less than 200 mrem/hr, waste package lifetime greater than 10,000 years.

EDA V Goal: Cladding less than 350°C, keep drifts dry for several thousand years, drift wall temperature less than 225°C.

²Assumed blending is such that the highest thermal output is not more than a given percentage greater than the average PWR waste package. It is 20 percent for EDAs I and II, and 50 percent for EDA V.

the comparison of EDAs, a common drip shield design (using the titanium alloy grade 7 [Ti-7]) was specified as the placeholder for defense in depth across all of the designs. Additionally, from this list, backfill, filler, and a dual corrosion-resistant materials waste package were chosen as elements to be evaluated in the EDAs. Each of these elements was included in at least one of the EDAs.

5.1.5.2 Waste Package Design

The reference waste package used in the Viability Assessment contained A516 carbon steel as a thick outer barrier and Alloy-22 as the inner barrier. During the period the LADS core team was considering the various DAs and DFs, evaluations indicated that there were two reasons for improving the Viability Assessment approach. First, the carbon steel degrades by oxidation. When the oxidation reaches the interface between the inner and outer barrier, the oxidation products of the steel along the crevice could wedge (force the separation of the layers), due to the large volume expansion of the oxide. This could create sufficient stresses between the two materials to cause the inner (thinner) Alloy-22 barrier to fail or to break off the remaining carbon steel outer barrier. Second, oxidation of the carbon steel reduces the structural strength of the waste package and its ability to resist rockfalls.

As a result, a design with 2 cm of Alloy-22 material placed on the outside of the waste package in most of the EDA designs was used to afford a much longer-lived primary barrier. Additionally, for all but EDA IV, the carbon steel was changed to a 5-cm-thick shell of stainless steel 316L (SS-316L), since this material does not produce large volume changes when it oxidizes. Performance assessment analyses indicated the combination of Alloy-22 and SS-316L should outperform the Viability Assessment design waste package when subjected to seepage water or rockfall (CRWMS M&O 1999l). The analysis assumed that the stainless steel does not provide a significant increase in the waste package lifetime once the Alloy-22 is breached; thus, no corrosion model was developed for crevice corrosion or stress corrosion cracking of the stainless steel. The EDAs also considered a dual corrosion-resistant material design for possible performance benefits and a 30-cm-thick A516 carbon steel waste package.

5.1.5.3 Ground Support and Invert Materials

The evaluation of ground support options considered unlined drifts, metal-lined drifts, and concrete-lined drifts (CRWMS M&O 1999q). Evaluation of postclosure performance with concrete-lined drifts showed that significant uncertainties exist. In this respect, postclosure uncertainties associated with the use of steel are considered small. Based on this evaluation, steel ground support was used in all of the EDAs. Due to the possibility of varying ground conditions, a variety of steel ground support methods may be required. Development of the details of the ground support are a subject of the detailed design. Based on the uncertainties for the use of cementitious materials in the drifts, the invert material selected for use in all of the EDAs was also steel. A granular material added as ballast to the steel can also serve as a diffusive barrier when used in conjunction with a drip shield.

5.1.5.4 Standardization of Drift Diameter for all Enhanced Design Alternatives

The objective of the drift diameter evaluation (CRWMS M&O 1999i) was to consider the various effects of drift stability, rock damage, seepage, thermal changes, and cost. Even though each of these attributes do change with drift diameter, none changes so significantly that an advantage is realized by independently specifying a smaller or larger diameter. Intermediate conclusions from the drift diameter evaluation include the following. Seepage and in situ stresses are not significantly affected by changes in drift diameter; drift stability increases slightly as diameter decreases from 5.5 m to 4.5 m. The drift wall temperature increases with

decreasing diameter; decreasing the diameter from 5.5 m to 4.5 m would result in a 22°C increase for the Viability Assessment design. Such a change in temperature could be important to achieving temperature goals. Costs appear to scale to the 0.7 power of the ratio of the diameter to the Viability Assessment diameter (for example, a 4.5 m drift is approximately 15 percent less costly than a 5.5 m drift). Thus, there would not be large cost savings by decreasing the drift diameter. As a result of this evaluation, the LADS core team standardized the drift diameter at 5.5 m for all EDAs.

5.1.5.5 Thermal Management

The major dimension distinguishing the five EDAs chosen for evaluation was the choice of thermal management strategies (i.e., whether [and how] the heat emitted by the waste would be used or controlled to enhance performance objectives or reduce uncertainties). All of the EDAs adopted goals on the temperatures of the spent nuclear fuel cladding and the drift walls. The EDAs differ significantly in the choice of whether to control the effects of heat even more strictly or to seek to make positive use of the heat in some way. For example, EDA I sought to keep all of the rock in the repository below the boiling point in order to limit the complications arising from boiling large quantities of water in the repository region. In contrast, EDA V sought to keep the entire repository area as hot as possible (while meeting the goals mentioned above) for as long as possible in order to prevent the onset of corrosion for an extended period.

Major features of the different EDAs represented choices about how to control the way the heat from the waste could affect the repository:

- **Waste package size**—Increasing the amount of spent nuclear fuel or high-level radioactive waste in a waste package increases its heat output. This could affect the maximum temperatures reached by the cladding of the fuel, the waste package surface, and the nearby rock. Other things being equal, smaller packages could make it easier to meet thermal goals in and immediately around the waste packages. They would have little effect on how the heat affected the rock some distance from the emplacement drifts. Using smaller packages would increase the number and total cost of the waste packages, the number of handling operations (although the smaller packages are easier to handle), and the length of the drifts required.
- **Blending**—Commercial spent nuclear fuel assemblies arriving at the repository would be expected to have a wide range of heat outputs, depending upon the amount of power extracted from them while they were in the reactor and the amount of time that had passed since the assemblies were removed from the reactor. (The higher the power, the more radioactive, heat-emitting atoms were created while the fuel was in the reactor. The older the fuel, the more of those atoms have spontaneously converted to other less- or non-radioactive atoms.) If the assemblies were loaded into waste packages as soon as they arrived, some waste packages could be loaded with mostly hot assemblies and others with mostly cool assemblies. This could lead to a wide variation in the heat outputs of different waste packages, which could, in turn, cause localized hot or cool

spots in the emplacement drifts. This could introduce potential performance issues and complications in the analysis of performance.

- "Blending" would involve holding some of the hotter fuel assemblies as they arrived until some cooler assemblies were available, so that some of the hotter assemblies could be combined with cooler ones in a waste package to reduce the overall heat output of the package. This would reduce the problems caused by wide variations in heat output, but would require some holding capacity and increases the complexity of the waste handling operations. As in the Viability Assessment design, fuel assemblies would only be handled once, and both the criticality and heat output of each assembly would need to be considered coupled with the other fuel assemblies proposed for the target package. Some assemblies might need to be held in the pool for a considerable time in order to best match the characteristics of that assembly with other compatible assemblies. As with the Viability Assessment, each waste package would become a part of an annual engineering analysis, and would be coupled with an analysis of the complete ongoing inventory of fuel assemblies that are being received. (The Viability Assessment design used limited blending. Fuel assemblies that exceeded a specified thermal output were simply placed in smaller packages containing fewer assemblies, to limit the total heat output of those packages.)
- The analysis of blending as a DF indicated that an increase in the planned capacity of the water basin in the fuel receipt facility could allow sufficient blending to reduce the variation in waste package heat outputs to 20 percent above or below the average heat output. This level of blending was assumed by all of the EDAs that incorporate blending.
- **Waste package spacing**—The closer the waste packages are placed to each other in the emplacement drifts, the more each is influenced by the heat emitted by its neighbors. This could increase the temperatures in and around the waste packages and the overall heating of the rock around the drifts. For example, the hotter the individual packages, the more difficult it would be to place them close together without exceeding the temperature limit on the cladding. The Viability Assessment design, which allowed waste package heat outputs as high as 18 kW, used a "point load" approach, in which the waste packages were spaced far enough apart that they can be analyzed as separate point sources of heat. At the other extreme is the "line load" approach, in which waste packages are put so close together that heat could be transferred from package to package, primarily by thermal radiation. While this would increase the temperatures in and around the packages, it would tend to even out the effects of differences in heat outputs among the packages, and simplify the analysis by allowing the packages in a drift to be treated as a uniform line source of heat instead of a large number of separate, non-uniform points. By greatly reducing the spacing between packages, the line load approach also reduces the length of drifts that must be constructed. Because of these advantages, all of the EDAs sought to use a line load, and all but EDA I were able to do so, while still meeting other thermal goals.

- **Drift spacing**—The closer the waste emplacement drifts, the hotter the rock midway between them can get, and the more the heat from one drift would affect the temperatures in its neighbors. If the drift spacing is small enough, all of the rock for some distance around the entire repository area will be heated above the boiling point of water. This should produce a “thermal umbrella” above the repository that would keep water out of the drifts for an extended period. Close spacing could also reduce the total amount of repository area needed for the disposal of any given amount of waste. Alternatively, spreading the drifts far enough apart so the centers of the pillars between them do not exceed the boiling point is expected to allow water (infiltrating from the surface or released from the pores of the rock by the heat from the waste) to drain around the drifts. The five EDAs represent a wide range of drift spacings.
- **Aging and ventilation**—The heat output of spent nuclear fuel and high-level radioactive waste declines as the waste gets older. Active ventilation of the loaded emplacement drifts can remove a substantial fraction of the heat emitted by the waste in the period before the potential repository is closed, making it easier to limit the postclosure peak temperatures in and around the waste packages. The Viability Assessment design includes a very low ventilation rate designed for radiation monitoring rather than thermal management. Because all of the EDAs either place the waste packages much closer together or have lower temperature goals than the Viability Assessment design, all require substantially higher ventilation rates to keep temperatures within the design limits. These higher ventilation rates involve the construction of additional or enlarged ventilation shafts and drifts, equipment and power sources designed to achieve high reliability for many years, and higher operating costs during the open period of the potential repository. In the initial analysis of candidate EDAs during the Phase I workshop, a number of the EDAs assumed that a combination of 25 years of aging and 25 years of post-emplacement ventilation would be needed to meet the thermal management objectives. Since further detailed analysis showed that all of the EDAs could meet their thermal goals with ventilation alone, the LADS team decided to include only post-emplacement ventilation to simplify the analysis and comparison of the EDAs. If an EDA using thermal management were selected, a trade-off study comparing the costs and benefits of the various thermal management techniques could be performed during the refinement of the design.

Each of the five EDAs evolved during the evaluation process and the resulting configurations are described in Section 5.3.

5.1.6 Use of Design Alternatives in Enhanced Design Alternatives

During the workshop and subsequent activities for selecting and improving EDAs, ideas from the DAs were used to create the EDAs. This section lists the major items covered by each of the DAs and describes where the ideas and concepts from these DAs were used in the EDAs. If they were not used, the rationale for excluding them is summarized.

5.1.6.1 Design Alternative 1–Tailored Waste Package Spatial Distribution

Percolation Flux–The concept of moving waste packages to relatively drier or wetter areas of the emplacement drifts, depending upon the content or robust nature of the waste package when exposed to certain environments, was appealing. Waste packages that have high thermal output could be placed in areas of high percolation flux, while those with low thermal output could be placed in areas of relatively lower percolation flux. Alternatively, certain waste packages could be made more robust to resist a higher percolation flux, or cost savings could be achieved by placing less robust waste packages in areas of low flux.

In reviewing the study on this subject, the LADS team concluded that the concept and the reality of the situation are not compatible. Data available and modeling techniques in use do not allow a distinction to be made on the level of percolation flux at any particular point in the Viability Assessment design footprint. Thus, the impact on the degradation of waste packages was also impossible to estimate.

DA 1 concluded that rearranging the waste packages within the Viability Assessment footprint would not be beneficial. EDA V moved all of the waste packages to a region of lower percolation flux outside of the Viability Assessment design footprint.

Unsaturated Zone Travel Time–The concept of distributing waste packages as a function of the distance to the water table and/or the zeolite content in the unsaturated zone was examined. The team evaluated the unsaturated zone transport performance as a function of these variables. For nonsorbing radioactive particles, the spatial variation of the anticipated travel times through the unsaturated zone, for the long-term average climate, is on the order of 500 years. This is not a significant enough variation to warrant recommending relocating specific waste packages, because the time scale of waste package failures is from 4,000 years to beyond 10,000 years. Travel times in the unsaturated zone for sorbing particles range from 50,000 to more than 1 million years, measured from the time radionuclides are first released from the waste package. This range of 50,000 to 1 million years for sorbing particles would be significant for peak dose, but not within the 10,000-year standard used as an evaluation criterion. Much of the range in sorbing particle travel time is due to the zeolite sorption. Although there are more zeolites in the northern half of the Viability Assessment design footprint, there is more hydrologic contact with the zeolites in the southern half, due to matrix-dominated flow within part of the unsaturated zone there.

This concept was not selected as the basis of an EDA, due to its limited effects during the first 10,000 years.

Hot Versus Cold Waste Package Segregation–The third concept involved the possibility of grouping waste package types into categories of hot, medium, and cold waste package regions in the repository. The thermal conditions at the edge of the characterized area—the outer limits of the emplacement area—were also considered in this concept. The purpose of this grouping was to mitigate the tendency of moisture to move from the rock surrounding the hotter waste packages to rock that was cooler. Instead, the selected EDAs use combinations of line loading and/or thermal aging and blending to achieve temperature goals. (EDA V considered the use of edge loading to achieve the design goal of keeping the drifts dry for thousands of years.)

Thus, the concept of using hot, medium, and cold segregation of packages was not selected as a means of achieving an EDA.

5.1.6.2 Design Alternative 2—Low Thermal Load

25 MTHM/Acre Waste Packages Containing 21 PWR Spent Nuclear Fuel Assemblies—Low thermal load provided for the separation of waste packages to prevent significant thermal communication. The use of the 25 MTHM/acre loading with the waste stream and waste package size used in the Viability Assessment design was the “one-off” for this DA. Using this concept, heat from nuclear decay would increase the temperature of the rock adjacent to the waste packages above the boiling point of water. This concept differed from the Viability Assessment design in that it provided pathways of rock below the boiling point of water through which the mobilized water could make its way past the repository horizon and down toward the saturated zone.

The lower thermal load concept was used in EDAs I and II. Although no EDA used an areal mass loading as low as 25 MTHM/acre, the low thermal effects concept was used with large waste packages in EDA II, which had an areal mass loading of 60 MTHM/acre.

25 MTHM/Acre with Smaller Waste Package (Waste Package Wall Temperature Less Than 80°C)—Limiting the temperature of the waste package was an extension of the low thermal load concept, which had two advantages: 1) allowing mobilized water to drain through pillars of the host rock that are at temperatures below 80°C, and 2) avoiding the thermal regime mode of Alloy-22 corrosion known as crevice corrosion.

During the workshop selection process, it was agreed that the 80°C temperature constraint is overly constraining. The cost of achieving this temperature, as well as the technical means to accomplish it, were viewed as unattainable. Therefore, this concept was not selected as the basis of achieving an EDA.

25 MTHM/Acre with Smaller Waste Package (Emplacement Drift Wall Temperature Less Than the Boiling Point of Water)—This concept was viewed as having a desirable and attainable goal for the low-temperature concepts. Although the exact thermal loading was not duplicated in an EDA, the goal was selected, and EDA I was structured to achieve this goal by a combination of lower areal mass loading, blending, and ventilation.

5.1.6.3 Design Alternative 3—Postclosure Ventilation

Open-Loop Postclosure Ventilation—This concept relied on the stability of the drift openings to remain open for thousands of years after the repository has been closed. In addition, it relied on natural convection airflow to provide cooling of the waste packages and to remove heat after the repository is sealed at closure. Waste packages would provide heat that could drive this cooling effect and sufficient elevation difference would also be present to aid air circulation. However, it was decided that having this air circulation would challenge the status of repository closure, which is legally required, while raising concerns over potential human intrusion. Thus, it would provide grounds for denial of a license.

Therefore, this option was not selected as the basis for an EDA.

Closed-Loop Postclosure Ventilation—This concept was proposed to provide for the removal of moisture and heat from the waste package areas. It relied on the stability of the drifts over thousands of years. The predictions made for this option relied on modeling the percolation flux and coupled thermal-hydrologic-pneumatic processes.

The LADS team considered the system design concept and the problems inherent in these assumptions: the physical situation in the mountain with a drift system that had areas where the variability in the pressure boundary was uncertain; the need for long-term predictability of drift opening stability; the time-dependent nature of thermal loading; and the need for reliable information about the evolution and distribution of the moisture so that system response can be adequately predicted.

Because this concept could not be developed as a viable engineering system, it was not selected as a basis for an EDA.

Open/Closed-Loop Postclosure Ventilation—This system used the host rock as a radiator to cool the drifts and potentially remove moisture from the system. Limited work was done on this concept. It was viewed as less effective from a heat-and-moisture-removal standpoint than either of the concepts above, and it suffered from some of the same weaknesses. It had lower efficiency because of the relatively low conduction of the rock mass. In addition, it relied on the stability of the drifts over the very long term, as well as on openings in the mountain, which would also provide a potential path for human intrusion.

Not only was this option not as promising as other potential methods, but it had many of the same difficulties as well. Therefore, this concept was not selected as a means of achieving an EDA.

5.1.6.4 Design Alternative 4—Enhanced Access

Shielded Waste Package—Shielded waste packages would allow direct human access for manual handling during emplacement, inspections, and maintenance if blast cooling were also used. The shielding options included removable neutron shielding for use during human access to the drifts. The LADS core team reviewed the need for human access and determined that the policy of the project is to emplace, maintain, and monitor without human access. However, provision should be made to maintain the flexibility for human access, should there be an off-normal or design basis event.

Human access provisions that consider such an off-normal case were evaluated as part of the EDA selection process.

Manned Inspection Vehicle—This vehicle would allow human access to emplacement drifts with unshielded waste packages, inspection of ground-support structures, and inspection and replacement of instrumentation in the emplacement drift. The LADS core team ruled out the normal use of human access for entry into the drifts as a means of inspection and maintenance, because repeated blast cooling would cause thermal fatigue of the drift walls.

The manned inspection vehicle was not selected as a basis for achieving an EDA.

5.1.6.5 Design Alternative 5–Modified Waste Emplacement Modes

Horizontal or Vertical Borehole Emplacements–These were viewed as potential methods to emplace waste while maintaining access to the drifts. While access to the emplacement drifts would be enhanced with this method, waste packages would be less accessible than with the in-drift emplacement methods. Waste package sizes would also have to be significantly decreased because of the heat effect from the waste on the wall of the borehole. Refinements in the construction technology would have to be made to construct large, stable openings for the horizontal borehole options.

The team determined that there were other adequate ways to provide performance and accessibility without resorting to borehole options. This concept was not selected as a basis for an EDA.

In-Trench Emplacement–This was also viewed as an option that was primarily for accessibility to the emplacement drift. The trench emplacement feature required a removable cover that could be placed over the waste package when access was required. This item was retained for consideration as either defense in depth or access, but it was not selected to be an integral part of the EDAs to be evaluated. (See Section 5.1.2.2 for information regarding considerations for human access.)

Short Cross-Drift Emplacement–This was another method of improving human access by shortening the length of the actual emplacement drift that needed to be traversed to reach an area in need of maintenance or other human effort. Although the team considered this emplacement mode in reviewing human-access needs, the lack of need for ongoing human access was the key factor in not selecting this option as a basis for an EDA.

Various Alcove Emplacements–Various alcove arrangements for emplacement were reviewed in the DA study. In previous work, as noted in the DA study, the short cross-drift had already been chosen as superior to any of these alcove arrangements. No further consideration of these other alcove arrangements was viewed as warranted by the team.

5.1.6.6 Design Alternative 6 and Design Alternative 7–The Viability Assessment Design and the Viability Assessment Design with Options

During the development of the EDAs, many elements from the Viability Assessment design were carried forward as key elements of the EDAs selected for further evaluation. All of the proposed EDAs evaluated by the LADS core team used some of the elements of the Viability Assessment design, with EDA IIIa (CRWMS M&O 1999x) most closely resembling the original Viability Assessment design (DOE 1998b). The major differences between EDA IIIa and the Viability Assessment design are as follows:

- **Waste package materials**–EDA IIIa used the corrosion-resistant material of the Viability Assessment design, Alloy-22, on the outside of the waste package and stainless steel 316L as the structural material inside the waste package (see Section 5.1.5.2).

- **Drift loading and spacing**—Although EDA IIIa used the same areal mass loading as the Viability Assessment design, this was modified by the use of closely spaced waste packages (line loading) instead of the larger spacing of the Viability Assessment design (point loading). Keeping the same areal mass loading, the drift spacing for EDA IIIa was widened to 56 m compared to 28 m for the Viability Assessment design. The closer waste package spacing in EDA IIIa reduced the temperature variation along the drift as hotter waste packages radiated some heat to the cooler waste packages. As noted below, significant ventilation would be required in the preclosure period since otherwise the overall temperature of the drift would increase.
- **Ventilation**—The Viability Assessment design used slight ventilation of the emplacement drifts ($0.1 \text{ m}^3/\text{s}$) during the preclosure period as a means of monitoring performance. To allow line loading without overheating the cladding, ventilation (2 to $10 \text{ m}^3/\text{s}$ for 50 years) is required for EDA IIIa.
- **Emplacement drift ground support and invert**—The Viability Assessment design reviewed the use of both concrete and steel design for emplacement drift ground support and the invert. The Viability Assessment noted the possibility for concrete to be excluded due to potential problems with uncertainty in long-term postclosure performance (DOE 1998b, Vol. 2, pp. 4-54, 4-56). The LADS core team selected steel for the drift emplacement ground support and invert to eliminate those uncertainties in postclosure performance of EDA IIIa and all of the EDAs evaluated (see Section 5.1.3).
- **Drip shield**—EDA IIIa used a drip shield to fulfill defense-in-depth requirements, as did all of the evaluated EDAs. The drip shield delays the time of corrosion initiation of Alloy-22. Use of a drip shield was one of the Viability Assessment options.
- **Backfill**—Although EDA IIIa did not use backfill, both EDA II and EDA IV made use of this option of the Viability Assessment design.
- **Ceramic coating**—The Viability Assessment design option of ceramic coating on the waste package was not used in any of the evaluated EDAs. Instead, as noted in Section 5.1.3, this feature was selected as a potential defense-in-depth feature.

5.1.6.7 Design Alternative 8—Modular Design/Phased Construction

DA 8 was assumed to be relatively independent of the evaluation carried out for the EDAs. Impacts of the recommended design must be factored into an updated modular design/phased construction study. The LADS project addressed this need by recommending that the modular design/phased construction study be updated to reflect the needs imposed by the recommended design (see Section 7.3) (CRWMS M&O 1999hh).

5.1.7 Design Features Not Selected for Enhanced Design Alternatives

All of the DFs described in Section 4 were considered during the EDA development and selection process. The selection process and the qualifying EDAs are described in Sections 5.1.1, 5.1.2, and 5.1.3. Several DFs were incorporated in one or more selected EDAs. This

section describes those DFs that were not incorporated into any of the EDAs, with a brief explanation of why they were excluded.

5.1.7.1 Getter Under the Waste Package

This DF may be composed of a fine-grain-sized material, such as apatite, that has an affinity for various radionuclides.

Performance analysis of the getter barrier indicated that a moderate enhancement to postclosure performance could be achieved with a thick layer of apatite. However, this would require an increase in the drift diameter to 6.5 m. Several other uncertainties concerning the sorption behavior of apatite were also considered:

- Dissolved materials in groundwater could be sorbed onto the getter before radionuclides release from the waste package, thus reducing the availability of sorption sites when the waste packages did breach.
- Competition for sorption sites between radionuclides and dissolved groundwater constituents after breach of the waste packages could diminish the getter's performance.
- In-drift colloids could pass through the engineered barrier system without sorption onto the getter.
- It is uncertain how long radionuclides would remain sorbed on the getter. Experiments indicate desorption occurs, but slower than adsorption. Thus, the getter can be expected to retard, but not permanently stop, radionuclide transport.
- Dissolution of the getter could occur prior to waste package breach.

This DF was not selected because of the uncertainties described above and the limited potential for improvement in postclosure performance.

5.1.7.2 Near-Field Rock Treatment During Construction

This DF required that fractures above emplacement drifts be grouted to reduce permeability and to divert water flow around them. Several grouting materials, including Portland cement, sodium silicate, bentonite, calcite slurry, and colloidal silica slurry, were considered.

An analysis concluded that the only promising material was calcite. The analysis also concluded that using calcite as the grouting material would result in only a minor reduction in the seepage of water into the drifts—7 to 8 percent at 500 years and 5 percent thereafter, through 100,000 years—at an estimated additional cost of \$500 million. This decrease in seepage would result in a negligible decrease in peak dose rate.

This DF was not selected because it had limited potential to improve postclosure performance and its cost was high.

5.1.7.3 Surface Modifications

This DF required that the surface of Yucca Mountain be altered in order to reduce water infiltration. Enhancement of drainage and the addition of alluvium were both considered.

An engineering analysis determined that the drainage option—the removal of thin alluvium less than 0.5 m thick—reduced net water infiltration on the ridge tops and slopes but increased the net infiltration in the washes. However, the improved drainage would overload the washes, resulting in an increased net infiltration there. Also, the increased runoff would seriously erode the washes and cause problems downstream.

For these reasons, the drainage option was not selected.

Another engineering analysis determined that the alluvium option—recontouring the surface above the repository and covering it with a layer of unconsolidated material—indicated a significant reduction in net infiltration. This could result in an improvement in repository performance, but it would require substantial grading and earth movement on the site above the repository, resulting in significant environmental impacts. In addition, the expected lifetime of the alluvium is uncertain.

For these reasons, the alluvium option was not selected.

5.1.7.4 Repository Horizon Elevation

This feature considered two concepts that involved a change in the repository horizon elevation. One concept was to move the repository horizon elevation; the second was to create a two-tier repository.

In the first concept, the repository horizon elevation was moved to allow more of the emplacement drift construction to be in the lithophysal zone. Thus, excavation in this zone could occur at a faster rate than in nonlithophysal zones, and the size of potential large block failures would be smaller. Placing the entire repository in the upper lithophysal zone was also evaluated, but the relatively steep grade of the formation caused this concept to be dropped from consideration.

Construction advantages from being in the lithophysal zone were offset by difficulties in transporting waste packages on a grade steeper than 3 percent. A variation of this concept was to move the repository 50 m higher so more of the construction would be in the lithophysal zone. This avoided the grade problem but resulted in less construction in the lithophysal zone. This variation showed some minor improvements in construction and in reducing potential key block size, but the advantages were offset by increased construction costs and schedule concerns.

This concept and its variations were dropped from consideration.

The second concept—a two-tier repository (one level directly above the other)—was thought to improve performance because the upper tier would act as an umbrella, thus limiting the amount of water that could percolate down to the lower tier. It was also thought that having two tiers

might allow for flexible waste emplacement strategies. For the umbrella concept to work, the two levels needed to be placed closer together than practicable from a construction standpoint.

This concept was dropped from further consideration, because the umbrella concept was not shown to be suitable.

During the EDA selection workshop, a variation of the two-tier design was proposed. This design used a broad drift above each pair of vertically stacked drifts to act as a percolation shield. This variation proved to be constructable, but it was not selected for further evaluation because of the difficulty of the construction and uncertainty in its performance.

5.2 ENHANCED DESIGN ALTERNATIVE EVALUATION CRITERIA

5.2.1 Introduction

During Phase II of the LADS project, each EDA was rated according to a set of evaluation criteria. The purpose of these criteria was twofold: 1) to provide a set of criteria that reflected the objectives; and 2) to discriminate among the designs and ultimately to assist in selecting a single design. As discussed in Section 3, and shown in Figure 3-2, the Phase I criteria were arrived at through an objectives hierarchy that identified fundamental objectives, termed "evaluation criteria," for this project. The fundamental objectives in Phase II were the same as those in Phase I, with the addition of two systems-level objectives: defense in depth and flexibility (Figure 3-3). The evaluation criteria for Phase II were consolidated into the following sets: performance demonstrability, construction/operations/maintenance, flexibility, and cost.

During Phase I, the DAs were intended to express basic design concepts, and the DFs were intended to be "one-off" concepts associated with Viability Assessment design. In contrast, the EDAs were to represent more complete conceptual designs and included various components to make them workable designs. As such, all had provisions for performance enhancement and for defense in depth. Consequently, the Phase II evaluation criteria included explicit consideration of performance margin and defense in depth. Another important Phase II criterion was termed "flexibility" and reflected the ability of a design to remain viable or changeable in the face of possible future programmatic or regulatory changes.

Each set of evaluation criteria consisted of multiple subcriteria that served to define it further. The subcriteria are measured on both natural quantitative scales (e.g., millirem/year) and constructed scales (e.g., 1 to 5). Importantly, the evaluation scores assigned to each subcriterion for each EDA were accompanied by documentation of the technical basis for each rating. As was the case with the evaluation criteria for Phase I, the constructed scales for the various subcriteria were not designed to allow meaningful mathematical combinations in a quantitative decision methodology. Rather, they provided guides to help the LADS core team perform consistent evaluations of the various EDAs when they were considered separately. As discussed in Section 6.1, the fundamental process for comparative evaluation of the EDAs was direct ranking of the EDAs with respect to each criterion, using a pair-wise comparison process in which the EDAs were compared two at a time. The relevant subcriteria scores for the EDAs being compared were used as the starting point for the discussion leading to a judgment by the team about the relative ranks of the EDAs on the criterion being considered. More important than the scores, the discussion considered the underlying technical reasons for the scores, documented in Section

5.3 and supporting references. Because the constructed scales do not have a numerical meaning, a "3" assigned to one subcriterion does not necessarily equate with a "3" on another subcriterion. Likewise, the fact that two EDAs might have been given identical scores on a particular subcriterion when the EDAs were evaluated separately does not imply that the LADS core team would necessarily conclude that they should be considered to be identical on that subcriterion when the EDAs were compared directly in the pair-wise analysis. The direct comparison considered all of the available information relevant to the EDAs' performance on that subcriterion, and reflected the insights that had been gained from the process of evaluating all of the EDAs separately. Section 6.2 documents the reasoning behind the ranking decisions that were made in the direct comparison process and Section 6.3 summarizes the ranking.

The Phase II EDA evaluation criteria were addressed by five EDA lead design engineers (one for each EDA), each supported by five core team leads. To ensure consistency in application of the criteria across all of the EDAs, a criterion lead (one for each of the four criteria) also participated. The criteria leads were responsible for clear and consistently understood definitions and measures for the criteria.

5.2.2 Enhanced Design Alternative Evaluation Criteria

Each of the Phase II evaluation criteria is given below. Ratings for all criteria, as well as their technical justification, are summarized in Section 5.3. The exact evaluation criteria and their measures used by the LADS core team in their evaluations are given below. They reflect the guidance provided by the criterion leads to clarify the criteria. The criteria provided to the EDA leads to focus their design efforts were slightly different (CRWMS M&O 1999aa).

Screening Criterion

The following screening criterion was determined by the LADS team to be necessary for any EDA to be considered as a candidate for selection as the conceptual design put forward as the initial design to be further developed for the Site Recommendation and possible License Application design. As such, this criterion was used to screen the EDAs. Any EDA that did not meet the screening criterion was to be removed from further consideration or was to be further enhanced to ensure that it met the screening criterion.

Postclosure Performance—Defined as the peak dose rate (central estimate) within 10,000 years to an average member of a critical group at a distance of 20 km from the repository. The screening criterion was 25 mrem/yr within 10,000 years. Note that longer-term performance was considered in the performance demonstrability evaluation criterion.

5.2.2.1 Performance Demonstrability

Assuming the site is found suitable and is approved by the President and Congress, the evaluation of performance demonstrability for the EDAs is based on a consideration of the performance margin, degree of defense in depth, and various factors related to the degree of engineering acceptance. The uncertainties in postclosure performance and the ability to reduce those uncertainties in the possible License Application time frame were also included in assessing the licensing probability.

To evaluate whether the design would lead to significant increases in the peak dose rate beyond 10,000 years, the performance up to 1 million years was also considered. The degree of defense in depth was an engineering judgment that multiple, diverse barriers existed that could lead to defense in depth. No EDA will lead to unacceptable environmental effects.

In addition, licensing probability was related to several factors defining the degree of engineering acceptance, as follows:

- The design function of each element could be clearly communicated.
- The engineering analysis followed accepted methods.
- The postclosure functions could be demonstrated.
- Precedents for the design and construction involved regulatory as well as engineering issues.
- The availability of qualified data was likely in the possible License Application time frame, or before waste emplacement begins.
- No high-level design goals for the Monitored Geologic Repository (i.e., goals listed in the requirements document [DOE 1999] and the assumptions document [CRWMS M&O 1998a]) were violated by the use of this design or, if violated, the consequence of the violation was acceptable, considering potential performance for the design.

Measures for the performance demonstrability criterion are:

- The performance margin, defined as the ratio between the screening criterion (25 mrem/yr) and the calculated 10,000-year performance (central estimate). The time when 25 mrem/yr would be reached is also calculated. In addition, the peak dose rate within 1 million years and the time of the peak were calculated.
- Defense in depth, as expressed by the number of principal barriers, and a constructed scale that expressed the degree of defense in depth associated with the design, based on a judgment of the effect that neutralization of each of the principal barriers would have on the dose rate within 10,000 years. This was also an expression of the ability of the design to mitigate the consequences of the uncertainties associated with individual barriers (i.e., 5 represents a high degree of defense in depth; 1 represents a low degree of defense in depth).
- A constructed scale that expressed the uncertainties in postclosure performance and the ability to reduce them within the possible License Application time frame (i.e., 5 represents small uncertainties or easily reduced uncertainties; 1 represents large, irreducible uncertainties). Uncertainties were expressed for three time frames: within 10,000 years; 10,000 to 100,000 years; 100,000 to 1 million years.

- A constructed scale that expressed the degree of engineering acceptance (i.e., 5 represents a high degree of acceptance; 1 represents a low degree of acceptance).
- A constructed scale that expressed particular advantages or disadvantages of the design relative to environmental effects (i.e., 5 expresses particular advantages; 1 expresses particular disadvantages).

Summary Evaluation—An overall evaluation that the design could evolve into a design that was acceptable for licensing in light of the 10,000-year dose, degree of defense in depth, postclosure uncertainties, 1-million-year peak dose rate, and engineering acceptance. The constructed scale ranged from 5 to 1, with the following descriptors as a guide:

<u>Rating</u>	
5	Highly likely
4	Reasonably likely
3	Equally likely as unlikely
2	Not likely
1	Highly unlikely

5.2.2.2 Construction, Operations, and Maintenance

This criterion was used to evaluate the particular advantages or disadvantages of an EDA in addressing construction, operations, and maintenance issues, including:

- Worker safety
- Constructability
- Operations
- Maintainability
- Handling logistics
- Performance confirmation activities
- Off-normal event recovery

Measures for the construction, operations, and maintenance criterion included a constructed scale that expressed the overall degree of advantage or disadvantage, taking into account the degree of simplicity or complexity in addressing construction, operations, and maintenance issues (i.e., 5 expresses highly advantageous; 1 expresses disadvantageous). Off-normal event recovery was expressed by the flow rate and duration of blast cooling required to allow human access, and the thickness and material for gamma and neutron shielding.

Summary Evaluation—A constructed scale that expressed the overall advantages or disadvantages of an EDA in addressing construction/operations/maintenance issues (i.e., 5 expresses significant advantages; 1 expresses significant disadvantages).

5.2.2.3 Flexibility

This criterion expressed the degree to which a design was capable of remaining viable, as well as its ability to change in the face of future regulatory, statutory, technical, or other changes. The LADS team considered the following possible changes:

- Increased disposal capacity (87,000 or 105,000 MTHM), if expanded capacity is authorized
- A longer preclosure period (100 or 300 years following emplacement)
- A shorter preclosure period (10 years following end of emplacement)
- Receipt of 5-year-old spent nuclear fuel
- Late design changes that were assumed to occur just prior to the start of construction (e.g., change from high to low areal mass loading, or vice versa, and adding or removing blending)
- Unanticipated natural features or findings (volcanism, seismicity, water table rise, flooding)

Measures for the flexibility criterion included a constructed scale that expresses the flexibility of the EDA to accommodate each of the possible contingencies (i.e., 5 expresses high degree of flexibility; 1 expresses low degree of flexibility).

Summary Evaluation—A constructed scale that expresses the overall flexibility of the EDA to accommodate all of the contingencies considered (i.e., 5 expresses high degree of flexibility; 1 expresses low degree of flexibility).

5.2.2.4 Cost/Schedule

Each EDA was evaluated for the time required and the present-day and discounted costs associated with each of the following phases: site characterization and licensing, construction, operations, monitoring, and closure.

Measures for the cost/schedule criteria were:

- The total repository life cycle costs (within –25 percent to +50 percent for conceptual design) associated with each of the five phases in 1998 dollars
- The net present value costs associated with each of the five phases⁶
- The number of years associated with each of the five phases (note that all estimates assumed a 50-year period, from start of emplacement to closure).

⁶ The net present value costs (1998 dollars) are calculated with a 2.3 percent real annual interest rate (net of inflation) based on economic assumptions used in analyses of the adequacy of the Nuclear Waste Fund (DOE 1998c).

5.3 ENHANCED DESIGN ALTERNATIVES EVALUATION SUMMARY

The evaluations of the five EDAs were made during a four-day meeting that involved the LADS core team, EDA lead design engineers, and criteria leads. During these meetings, the EDA design leads presented the current version of each EDA. The discussions centered on the evolution of the EDAs, the design trade-offs made, and the strengths and weaknesses of each design. Following each presentation and discussion, the LADS core team used the criteria presented in Section 5.2.2 to rate each EDA.

Mobilization of water from shedding and refluxing is an important process to consider in evaluating repository performance. Shedding is the movement of water around the drifts and down through the repository rock. When the drift wall temperature exceeds the boiling point of water, the pore water in the rock vaporizes, moves to the fractures, and travels away from the drift wall, thus keeping the region immediately around the drift dry. By not allowing the rock temperature in the region between the drifts (called pillars) to exceed this boiling temperature, water can be shed (or flow by gravity) around the drifts. If the water above the drift boils, it changes phases and is transported as vapor to a cooler region further above the drift. When the water vapor encounters this cooler rock, it condenses, and the resulting liquid water drains back down toward the hotter rock. This up and down movement of water caused by water changing from liquid to vapor and back is known as refluxing. Because water is responsible for waste package corrosion, radionuclide mobilization and transport, an understanding of the movement and transport of water in the repository rock is important.

NOTE: At the elevation of the repository, the normal boiling point of water is 96°C (not considering chemical or capillary effects); at sea level, water boils at 100°C.

Coupled processes, or the processes and implications of the thermal perturbation associated with emplacement of waste in the potential repository, are also important to consider in evaluating repository performance. Thermal, hydrologic, mechanical, and chemical processes are of potential importance to performance assessment issues as well as design issues (e.g., rock stability through the thermal period, changes in hydraulic properties due to dissolution and precipitation of minerals, changes in fracture-matrix interaction, etc.).

In the development and performance assessment modeling of the EDA designs, the total system performance assessment model used for the Viability Assessment was the starting point. Because some of the process models had evolved during the Viability Assessment period, there were some differences between the Viability Assessment model and the LADS model. In addition, the LADS project, because of the need to analyze such a large range of options, used central estimate calculations in which most performance assessment variable ranges were reduced to single values. A number of assumptions common to all of the designs were made in the performance assessment calculations (CRWMS M&O 1999kk) referenced in the EDA reports (CRWMS M&O 1999v through 1999z). The most significant assumptions were:

- Except for EDA V, closure 50 years after first waste package emplacement (defined as 2060, with emplacement assumed to begin in 2010).

- Removal of 50 percent of the heat generated by the waste packages, during periods of ventilation. This assumption was substantiated by design calculations during the EDA evaluations.
- Juvenile failure, defined as one patch (310 cm²) on one commercial spent nuclear fuel waste package at 1,000 years under the first drip shield that fails due to corrosion.
- In order to provide conservatism for defense in depth and performance analysis, all waste package barriers were neutralized together to address potential common mode failures.
- A window of susceptibility for the initiation of localized (crevice) corrosion of the Alloy-22 waste package, having an upper temperature threshold of 125°C and lower threshold of 85°C, with relative humidity greater than 80 percent; this is a simplification of the probabilistic performance assessment representation. The chemistry of the water is also a key factor in corrosion susceptibility.
- No localized corrosion of the drip shield.

In addition to these assumptions, the EDAs also shared common design elements, such as the Viability Assessment waste stream and repository capacity, 5.5-m drift diameter, 2-cm Ti-7 drip shield, repository horizon within the Topopah Spring tuff unit (see Figure 5-1), and preclosure ventilation of 2 to 10 m³/s in the emplacement drifts for 50 years. The drip shields would be placed over the waste packages just before closure of the repository. Deferring emplacement for as long as possible reduces the impact of the cost of the drip shields on the net present value of the repository costs, and allows for improving the design before actual emplacement. Some of these common features could create difficulties in construction, operations, and maintenance and add additional cost to the repository. The fact that they are common means that these issues did not play a role in discriminating among the EDAs.

Note that in evaluating the flexibility criterion, the LADS core team concluded that all of the EDAs provided the same degree of flexibility relative to unanticipated features or findings, and the criterion was not further evaluated.

The design values used for each EDA are summarized in Table 5-4. These values differ from those initially assumed for the EDAs in Table 5-3 due to adjustments made during the course of design development. The number of waste packages in EDAs II and V is slightly smaller than for EDAs III and IV because the higher degree of blending reduces the number of 12 PWR waste packages and increases the number of 21 PWR waste packages.

The EDAs used features of the DAs and DFs. However, it should be noted that the DA and DF reports were based on the changes related to the Viability Assessment design (one-off concept). Using combinations of features and alternatives resulted in designs for the EDA development that materially changed some of the fundamental arguments of the DA and DF reports. Thus synergies were created that were neither evident nor evaluated by the one-off concept. While there may appear to be a conflict in the results of the one-off concept compared with the EDA concept, there is, in fact, none. It should not be expected that the results of the EDA evaluations will reflect those of the Phase I DF and DA reports.

Table 5-4. License Application Design Selection Enhanced Design Alternatives—Design Values

Design Element	EDA I	EDA II	EDA III	EDA IV	EDA V
Thermal Goals					
• Cladding	350°C	350°C	350°C	350°C	350°C
• Waste package surface			Cools to 80°C before relative humidity reaches 90%		
• Drift wall	96°C	200°C	200°C	200°C	225°C
• Drift environment				Keep drifts dry for thousands of years	Keep drifts dry for several thousand years
• Pillar temperatures		Keep centers of pillars below boiling (96°C)			
• Other goals				Limit gamma dose at waste package surface to 200 mrem/hr	
Areal Mass Loading (MTHM/acre)	45	60	85	85	150
Area (acres) for 70,000 MTHM ¹	1,400	1,050	740	740	420
Line/Point Load	Point	Line	Line	Line	Line
Waste Package Size (PWR)	12	21	21	21	21
Drift Diameter (m)	5.5	5.5	5.5	5.5	5.5
Drift Spacing (m)	43	81	56	56	32
Preclosure Ventilation	50 years @ 2 to 10 m ³ /s	50 years @ 2 to 10 m ³ /s	50 years @ 2 to 10 m ³ /s	50 years @ 2 to 10 m ³ /s	50 years @ 2 to 10 m ³ /s
Waste package heat output at emplacement	20% blending used to reduce maximum	20% blending used to reduce maximum	Limited blending	Limited blending	20% blending used to reduce maximum
Maximum	6.7 kW	11.8 kW	18.0 kW	18.0 kW	11.8 kW
Average (PWR waste package)	5.6 kW	9.8 kW	9.5 kW	9.5 kW	9.8 kW
Waste Package Material	2-cm Alloy-22 over 5-cm stainless steel	2-cm Alloy-22 over 5-cm stainless steel	a) 2-cm Alloy-22 over 5-cm stainless steel b) 2-cm Alloy-22 over 1.5-cm Ti-7 over 4-cm stainless steel	30-cm carbon steel	2-cm Alloy-22 over 5-cm stainless steel
Fillers	No	No	No	Integral filler	No
Backfill	No	Yes	No	Yes	No
Drip Shield	Yes	Yes	Yes	Yes	Yes
Total Waste Packages	15,903	10,039	10,213	10,213	10,039

¹ Areas are calculated by dividing the commercial inventory (63,000 MTHM) by the areal mass loading and rounding to the nearest 10 acres; additional area would be required for perimeter drifts, maintenance drifts, and contingency areas.

A brief description, the ratings and their technical bases, and a cost estimate for each EDA are provided in Sections 5.3.1 through 5.3.5.2. The use of the evaluation for making the EDAs is discussed in Section 6.1.

5.3.1 Description of Enhanced Design Alternative I

EDA I was a low-temperature concept (CRWMS M&O 1999v), the lowest of the five EDAs. The purpose for considering a low-temperature design was to remove the uncertainties and modeling difficulties associated with above-boiling temperatures (temperatures greater than 96°C, the boiling point of water at the repository altitude). Lower temperatures mean less disturbance to the subsurface environment. Reducing heat-induced alterations of the natural barriers should also reduce the uncertainties about performance in the very long term after the temperatures in the potential repository have returned to levels close to what existed before the waste was emplaced. This EDA would eliminate the phase change that occurs at the boiling temperature of water and would limit the coupled effects of thermal, hydrological, and geochemical processes that are often more pronounced in above-boiling temperature environments. Also, the period of time that the waste packages would experience temperatures close to the boiling point of water would be relatively short (hundreds of years following closure), followed by cooler temperatures. A thermal calculation for this EDA found that the peak drift wall temperature of 94°C occurred about 300 years after closure. This temperature regime would place waste packages in a relatively benign environment.

The goals of EDA I were to ensure that the drift wall temperatures remain below the boiling point of water and to keep the fuel cladding inside the waste packages below 350°C. There was no temperature goal for the surface of the waste package. These goals were achieved for the EDA I design by limiting the areal mass loading to 45 MTHM/acre, increasing the size of the potential repository to 1,400 acres (most of the area that has been characterized to date), and using smaller waste packages. The drift spacing was 43 m from the drift centerlines, with an average end-to-end waste package spacing of 3 m. In this design, drift spacing was a relatively insensitive factor; the critical factor was the spacing between waste packages. Preclosure ventilation for this EDA would use two intake air shafts and three exhaust shafts in addition to the access tunnels.

In order to limit the heat output of the waste packages for the thermal goals specified, EDA I used smaller waste packages for commercial spent nuclear fuel than the other EDAs. The selected waste package size was the 12 PWR, 24 boiling-water reactor size. The waste package design for this EDA consisted of two layers, with Alloy-22 on the outside and SS-316L on the inside (see Figure 5-2). EDA I used point loading to take advantage of the flexibility in waste package spacing to control the drift temperature. Blending would reduce the maximum thermal output from a waste package to 6.7 kilowatts. A 2-cm-thick Ti-7 drip shield was included with the design to provide defense in depth for the postclosure performance (see Figure 5-3). Because of its low preclosure temperatures, EDA I could be amenable to allowing human access to the drifts and waste packages in the case of an off-normal event. Human access would be possible by blast cooling (20 m³/s) a single drift and by the selective placement of portable shielding

(a steel shield 15 cm thick for gamma radiation and a borated polyethylene shield 7.5 cm thick for neutron radiation).

One of the primary disadvantages of this design was that it used all of the available space in the upper emplacement level of the repository (see Figures 5-1 and 5-4). Another disadvantage is the use of smaller waste packages (12 PWR, 24 boiling-water reactor, and 5 PWR [long]). This EDA required about 6,000 more waste packages than the other EDAs. The DOE spent nuclear fuel and high-level radioactive waste was not assumed to be placed in waste package sizes different from the Viability Assessment design. Further development of EDA I would require a study of the waste package size for this waste stream component.

EDA I had waste package temperature and humidity histories that did not enter the Alloy-22 crevice corrosion window of susceptibility, defined as temperatures between 85 and 125°C while relative humidity is above 80 percent (see Figures 5-5 and 5-6). The performance assessment calculations (thermal, waste package failure, and dose rate) were based on 25 years of aging and 25 years of ventilation with 50 percent of the waste thermal power being removed during the ventilation period (CRWMS M&O 1999kk).

5.3.1.1 Enhanced Design Alternative I Evaluation Summary

A summary of the evaluation of EDA I, based on the criteria described in Section 5.2, is provided below. The postclosure performance predictions presented under "Screening Criterion" and "Performance Demonstrability" are based on Figures 5-7 and 5-8, and were derived from the calculations contained in the performance assessment calculations (CRWMS M&O 1999kk).

Screening Criterion

The postclosure performance prediction of 0.01 mrem/yr is well below the 25 mrem/yr screening limit, for the screening period of 10,000 years.

Performance Demonstrability

Performance Margin—Based upon the predicted performance and screening limit, the performance margin ratio for EDA I is 2,500. The peak dose rate is 85 mrem/yr at 320,000 years. It would take 290,000 years to reach the screening dose limit of 25 mrem/yr. The 10,000-year dose rate is entirely due to an assumed juvenile failure of one waste package; the first calculated waste package failure from corrosion was at about 100,000 years.

Defense in Depth—In addition to the natural barriers, EDA I had four principal barriers (i.e., the Alloy-22 and SS-316L layers of the waste package, the fuel cladding, and the drip shield). Defense in depth for the first 10,000 years was evaluated by computationally removing (neutralizing) the waste package barriers. This simple neutralization estimate could be repeated for each of the other barriers included in the EDA. Based on the expected results of these neutralization estimates for the engineered barriers, the design for EDA I was given a rating of 3, which indicates its ability to mitigate the consequences of uncertainties in the individual barriers.

Uncertainties in Postclosure Performance—Within the first 10,000 years, uncertainties in the postclosure performance were reduced in the design by avoiding significant modification of the

surrounding rock (e.g., coupled thermal-hydrological processes were minimized). The amount of time in the aggressive corrosion regime (greater than 85°C) would be short (a few hundred years). The need for models that reflect coupled processes, localized corrosion mechanisms, and other complex mechanisms is significantly reduced for this EDA. The rating for the uncertainty in the first 10,000 years was 4.

Within the first 100,000 years, no waste package failures (other than the baseline juvenile failure) were calculated. Because there would be much less disturbance of the environment, there would be greater confidence in estimating the environment following the postclosure thermal peak. There are fewer corrosion issues (such as stress corrosion cracking and pit repassivation) during this period and hydrogen embrittlement of the Ti-7 drip shield is unlikely. The rating for the uncertainty in the 10,000- to 100,000-year time frame was 3.

Within the first million years, there are large irreducible uncertainties in long-term corrosion rates, long-term coupled processes, and natural system characteristics. The ability to predict performance over such a long time period is highly uncertain. The rating for the 100,000- to 1-million-year time frame was 1.

Engineering Acceptance—It would be easier to demonstrate the postclosure function in EDA I because there is less concentration of heat and the aggressive corrosion times are shorter. All elements of the design have engineering precedents. The rating was 3.5.

Environmental Considerations—The LADS core team found no areas of significant environmental concern for this EDA. The rating was 3.

Construction, Operations, and Maintenance

Worker Safety—This EDA would require the construction of many more drifts and more emplacement operations, which could increase the possibility of industrial accidents. The rating was 2.

Constructability—There were no unusual issues. The rating was 3.

Operations—There were no unusual issues related to drip shields or the placement of waste packages, or waste package sequencing. Blending would be required. The rating was 3.

Maintainability—There were no unusual issues. The rating was 3.

Handling Logistics—There would be a larger number of waste packages compared with the other designs, but the smaller size would be easier to handle. The rating was 2.5.

Performance Confirmation—Because the temperatures would be lower, the emplacement drifts offered a less hostile environment. Therefore, it may be possible to eliminate the performance confirmation drifts and install the necessary instrumentation in the emplacement drifts. If this EDA were selected, the difficulty in placing the instrumentation in the harsh environment of the emplacement drifts versus the cost of performance confirmation in separate drifts would require further study. The rating was 4.

Off-Normal Events—Blast cooling of a single drift to allow human access would require about 20 m³/s of ventilation for one week based on extrapolation from a higher temperature design calculation (CRWMS M&O 1995b). Portable shielding for radiation protection would need to consist of about 19 cm of steel and 10 cm of borated polyethylene (CRWMS M&O 1999jj).

Flexibility

Increased Capacity (If Authorized)—In order to accommodate 87,000 MTHM, about 25,000 waste packages and 1,930 acres would be required. This capacity could be accommodated in the characterized area, but with less contingency area than is used in the Viability Assessment design and other EDAs. To accommodate 105,000 MTHM, about 29,000 waste packages and 2,330 acres would be required. This increased number of waste packages could not be accommodated in the characterized area, and additional area would need to be characterized. The rating was 2.5.

Preclosure Period—Closure extended 100 to 300 years: This could easily be achieved. The rating was 4.

Closure 10 years after emplacement ends: The drift temperatures for this EDA were close to the drift wall thermal goal with closure at 50 years; maintaining the thermal goals may be difficult under early closure. It is unlikely that EDA I could meet this requirement without significant modification. The rating was 2.

Change in Commercial Spent Nuclear Fuel Characteristics—Five-year-old commercial spent nuclear fuel arriving at the repository site late in the life of the repository would pose a problem for thermal management, particularly with respect to drift wall temperature. The rating was 2.

Late Design Changes—Thermal design change (cold to hot): Changing to a high thermal load design could not be easily accommodated because the modeling and other analyses conducted for a lower temperature environment would likely not cover higher temperatures effects and these would be difficult to “add on” unless the needed work were performed in parallel. The change could be accommodated by moving drifts closer together and making changes in waste package size and in the subsurface layout from point loading to line loading. The rating was 1.

Eliminating blending: Blending is an integral part of EDA I. The elimination of blending would require the use of other thermal management tools such as package derating, a larger repository area, aging, or higher ventilation. The rating was 2.

5.3.1.2 Cost/Schedule

The cost/schedule estimate for EDA I is presented in Table 5-5. These values are a rough order of magnitude (–25 percent and +50 percent) for conceptual design (CRWMS M&O 1999II, p. 14). See Section 5.3.7 for comparable Viability Assessment design costs.

Table 5-5. Cost Estimate for Enhanced Design Alternative I

Phase	Licensing Period (2002-2005) ¹	Construction Period (2005-2010) ¹	Operations Period (2010-2033) ¹				Monitoring Period (2033-2060) ¹	Closure Period (2060-2066) ¹			Total Cost
			Under-ground	Ventilation	Waste Package	Other		Drip Shield	Backfill	Other	
LCC	\$0.8	\$3.7	\$4.1	\$1.1	\$5.0	\$3.7	\$1.8	\$4.0	NA	\$0.8	\$25.1
NPV	\$0.7	\$3.0	\$2.4	\$0.7	\$2.9	\$2.0	\$0.6	\$0.9	NA	\$0.2	\$13.4

Key:LCC: Repository life cycle cost in \$billion
¹Assumed dates

NPV: Net present value in \$billion

NA: Not applicable

5.3.2 Description of Enhanced Design Alternative II

EDA II was a low thermal effects design (CRWMS M&O 1999w). The emplacement area encompassed 1,050 acres in the upper emplacement level of the characterized area (see Figures 5-1 and 5-9). The waste package design for this EDA, like EDA I, consisted of two layers, with Alloy-22 on the outside and SS-316L on the inside. The goals for EDA II were to keep the fuel cladding temperature below 350°C and keep the boiling fronts from coalescing in the pillars between drifts (see Figure 5-10). The latter goal ensured that there would be sufficient portions of the pillar temperatures below the boiling point (temperatures less than 96°C, the boiling point of water at the potential repository's altitude) to allow water to drain through the pillars when the adjacent rock is above the boiling point of water. These goals were achieved with an areal mass loading of 60 MTHM/acre provided by closely-spaced (10 cm spacing) waste packages, line loading, and a drift spacing of 81 m. In addition, this EDA included backfill and a 2-cm Ti-7 drip shield over the waste package at closure to provide defense in depth for postclosure performance. The backfill would be placed over the continuous drip shield after it had been installed over the waste packages before closure. (The backfill must be emplaced as late as possible to avoid overheating of the fuel cladding.) The backfill provides added protection against rockfall and avoids temperature/humidity conditions conducive to aggressive crevice corrosion of Alloy-22. Blending would reduce the maximum waste package heat output to within 20 percent of the average heat output of 9.8 kilowatts, thus allowing closure at 50 years. Continuous ventilation at the rate of 2 to 10 m³/s in the emplacement drifts would be required for the 50-year preclosure period.

An advantage of this EDA is that water mobilized by temperatures higher than boiling in the rock near the emplacement drift would be diverted to drain through the cooler pillars between the drifts rather than collecting above the emplacement drift. The boiling fronts created by the water being driven away from the drifts by the above-96°C temperatures are not expected to coalesce in this design. The very wide spacing of the drifts, coupled with preclosure ventilation and blending of the waste packages, eliminates the possibility of this coalescence. Because the drifts of EDA II are more thermally independent than in the Viability Assessment design, the data from the drift scale test will be more representative of repository conditions. It may allow the potential repository to be analyzed as a collection of independent drifts without requiring analysis of the complex effects of heat over the entire repository area.

A disadvantage of EDA II is that it has not been demonstrated that some condensate would not drain back into the drift.

EDA II had waste package temperature and humidity histories that did not enter the Alloy-22 crevice corrosion window of susceptibility, defined as temperatures between 85 and 125°C while relative humidity is above 80 percent. The performance assessment calculations (thermal, waste package failure, and dose rate) were based on 25 years of aging and 25 years of ventilation with 50 percent of the waste's thermal power being removed during the ventilation period. A second thermal calculation was done with no aging and 50 years of ventilation; the result was closer approach of the thermal histories to the susceptibility window, but with no time actually within the window (see Figures 5-11 and 5-12) (CRWMS M&O 1999kk).

5.3.2.1 Enhanced Design Alternative II Evaluation Summary

A summary of the evaluation of EDA II, based on the criteria described in Section 5.2, is provided below. The postclosure performance predictions presented under "Screening Criterion" and "Performance Demonstrability" are presented in Figures 5-13 and 5-14, and were derived from the calculations contained in the performance assessment calculations (CRWMS M&O 1999kk).

Screening Criterion

The postclosure performance prediction of 0.007 mrem/yr is well below the 25 mrem/yr screening limit, for the screening period of 10,000 years.

Performance Demonstrability

Performance Margin—Based upon the predicted performance and screening limit, the performance margin ratio for EDA II is 3,550. The peak dose rate is 85 mrem/yr at 620,000 years. It would take 310,000 years to reach the screening dose limit of 25 mrem/yr. The 10,000-year dose rate is entirely due to an assumed juvenile failure of one waste package; the first calculated waste package failure from corrosion was at about 100,000 years.

Defense in Depth—In addition to the natural barriers, EDA II had five principal barriers (i.e., the Alloy-22 and SS-316L layers of the waste package, the fuel cladding, the drip shield, and the backfill). Defense in depth for the first 10,000 years was evaluated by computationally removing the waste package barriers. This simple neutralization estimate will be repeated for each of the other barriers included in the EDA. Based on the expected results of these simple neutralization estimates for the engineered barriers, the design for EDA II was given a rating of 3, which indicates its ability to mitigate the consequences of uncertainties in the individual barriers.

Uncertainties in Postclosure Performance—Within the first 10,000 years, EDA II has lower postclosure uncertainties because the drift wall temperature would not exceed 150°C, thus limiting adverse impacts to the surrounding rock by reducing thermal expansion and contraction and development of new fractures. Likewise, uncertainties are reduced regarding the potential for large-scale refluxing due to thermal interaction of the drifts in the hotter designs. Seepage would be high in this design and, although water should be shed around the drifts, some flow paths may intersect the drifts. There are also uncertainties in the performance of the backfill related to prediction of the temperature and relative humidity effects on the drip shield and backfill. The rating for the uncertainty in the first 10,000 years was 2.5.

Within the first 100,000 years, if the backfill does not perform as expected, the thermal condition within the emplacement drift would change and the drip shield would fail faster than predicted (similar to the performance of EDAs I, III, and V, which do not have backfill). The rating for the uncertainty in the 10,000 to 100,000 year time frame was 2.

Within the 100,000- to 1-million-year time frame, there are large irreducible uncertainties in long-term corrosion rates, long-term coupled processes, and natural system characteristics. The ability to predict performance over such a long time period is highly uncertain. The rating for the uncertainty in this time frame was 1.

Engineering Acceptance—The use of backfill to control the relative humidity and to protect the drip shield has no precedent, but there are precedents for the function of mitigating the effects of rockfall. There are precedents for blending, such as core reloads conducted at reactors. The rating was 2.5.

Environmental Considerations—The LADS core team found no areas of significant environmental concern for this EDA. The rating was 3.

Construction, Operations, and Maintenance

Worker Safety—There were no unusual issues. The rating was 3.

Constructability—Backfill emplacement may be difficult. The rating was 2.5.

Operations—Blending, coupled with the possibly difficult backfill emplacement, increases the complexity of operations in this EDA. The rating was 2.

Maintainability—There were no unusual issues. The rating was 3.

Handling Logistics—There were no unusual issues. The rating was 3.

Performance Confirmation—There were no unusual issues. The rating was 3.

Off-Normal Events—Blast cooling of a single drift to allow human access would require about 100 m³/s of ventilation for one week based on extrapolation from a higher temperature design (CRWMS M&O 1995b). Portable shielding for radiation protection would consist of about 19 cm of steel and 10 cm of borated polyethylene (CRWMS M&O 1999jj).

Flexibility

Increased Capacity (If Authorized)—In order to accommodate 87,000 MTHM, this EDA could readily expand within the characterized area, requiring about 1,400 acres. To accommodate 105,000 MTHM, this EDA could expand further into the characterized area requiring about 1,700 acres (see Figure 5-1). This increased capacity would require both the upper and lower emplacement levels. The rating was 4.

Preclosure Period—Closure extended 100 to 300 years: This can easily be achieved. The rating was 4.

Closure 10 years after emplacement ends: Because the cladding temperature goal may be exceeded, it is unlikely that EDA II could meet this requirement without significant modification. Backfill would exacerbate this problem. The rating was 1.

Change in Commercial Spent Nuclear Fuel Characteristics—Five-year-old commercial spent nuclear fuel arriving at the repository site late in the life of the repository would pose a problem for thermal management, particularly with respect to cladding temperature. The rating was 2.

Late Design Changes—Thermal design change (cold to hot): Moving the drifts closer together would result in higher temperatures. However, performance modeling and other analytic tools used for lower temperature analyses would probably not be useful in predicting high-temperature effects. The new predictive capabilities would be difficult to “add on” unless the work had been carried on in parallel. The rating was 2.

Eliminating blending: Blending is an integral part of EDA II. The elimination of blending would require the use of other thermal management tools, such as package derating, aging, or higher ventilation. The rating was 2.

NOTE: During preparation of this report, it was noted that EDA II could transition to the goals of EDA I, if a longer ventilation duration is used and backfill is not installed. This flexibility feature was not scored.

5.3.2.2 Cost/Schedule

The cost/schedule estimate for EDA II is presented in Table 5-6. These values are a rough order of magnitude (–25 percent and +50 percent) for conceptual design (CRWMS M&O 1999II, p. 14). See Section 5.3.7 for comparable Viability Assessment design costs.

Table 5-6. Cost Estimate for Enhanced Design Alternative II

Phase	Licensing Period (2002-2005) ¹	Construction Period (2005-2010) ¹	Operations Period (2010-2033) ¹				Monitoring Period (2033-2060) ¹	Closure Period (2060-2066) ¹			Total Cost
			Under-ground	Ventilation	Waste Package	Other		Drip Shield	Backfill	Other	
System	All	All					All				
LCC	\$0.8	\$3.2	\$1.9	\$0.4	\$4.1	\$4.3	\$1.6	\$3.3	\$0.4	\$0.5	\$20.6
NPV	\$0.7	\$2.6	\$1.1	\$0.2	\$2.4	\$2.5	\$0.6	\$0.8	\$0.1	\$0.1	\$11.0

Key:

LCC: Repository life cycle cost in \$billion

NPV: Net present value in \$billion

¹Assumed dates

5.3.3 Description of Enhanced Design Alternative III

EDA III is a high thermal load design (CRWMS M&O 1999x). Two designs with different waste packages were considered (EDAs IIIa and IIIb). The EDA IIIa waste package consists of two layers, with 20-mm Alloy-22 on the outside and 50-mm SS-316L on the inside. The EDA IIIb design uses a waste package with an outer layer of 20-mm Alloy-22 over 15-mm Ti-7, which have been shrink-fitted together. The inner structural layer is composed of 40-mm SS-316L that fits loosely inside the Alloy-22/Ti-7 shell. The gap between the two layers is less

than 4 mm. This inner shell provides structural support for the waste package (see Figure 5-15). In an attempt to minimize the operational aspects of the repository, the waste packages in EDAs IIIa and IIIb would be filled as the waste is received (limited blending, as in the Viability Assessment design). EDA III would require 740 acres in the upper emplacement level of the characterized area (see Figures 5-1 and 5-16).

The goals of EDA III were to limit the drift wall temperature to 200°C, limit the fuel cladding temperature to 350°C, and ensure that the waste package surface temperatures cool to below 80°C before the relative humidity at the waste package surfaces rises above 90 percent. (During the development of the EDAs, the window of susceptibility was revised to temperatures between 85 and 125°C while the relative humidity is above 80 percent.) These goals were met with 85 MTHM/acre loading, close (10 cm) spacing of the line-loaded waste packages (see Figure 5-17), and a drift spacing of 56 m between the centerlines. Ventilation for a minimum of 50 years, at a rate of 2 to 10 m³/s in the emplacement drifts, would be necessary to achieve the temperature goals of this EDA. This EDA also uses a Ti-7 drip shield.

An advantage of EDA III is that the surface of the waste package is predicted to cool to below 80°C before the relative humidity returns to 90 percent, thus avoiding the worst of the corrosive, warm-moist environment after closure. This design also allows continuous water shedding through the pillars between the drifts after the thermal boiling fronts recede.

The disadvantages of EDA III are the uncertainties associated with temperatures above 96°C. The design goals can be met for average waste packages with spent nuclear fuel; however, larger spacing between waste packages or longer cooling may be required to ensure the temperature goals are met for the hotter waste packages.

Most of the EDA III waste packages had temperature and humidity histories that entered the Alloy-22 crevice corrosion window of susceptibility, defined as temperatures between 85 and 125°C while relative humidity is above 80 percent (see Figures 5-18 and 5-19). The performance assessment calculations (thermal, waste package failure, and dose rate) were based on no aging and 50 years of ventilation with 50 percent of the waste thermal power being removed during the ventilation period.

5.3.3.1 Enhanced Design Alternative III Evaluation Summary

A summary of the evaluation of EDA IIIa, based on the criteria described in Section 5.2, is provided below. The summary for EDA IIIb follows that of EDA IIIa. The postclosure performance predictions presented under "Screening Criterion" and "Performance Demonstrability" were derived from the calculations contained in the performance assessment calculations (CRWMS M&O 1999kk).

SUMMARY FOR EDA IIIa

Performance evaluations are based on Figures 5-20 and 5-21.

Screening Criterion

The postclosure performance prediction of 0.017 mrem/yr is well below the 25 mrem/yr screening limit, for the screening period of 10,000 years.

Performance Demonstrability

Performance Margin—Based upon the predicted performance and screening limit, the performance margin ratio for EDA IIIa is 1,500. The peak dose rate is 215 mrem/yr at 720,000 years. It would take 290,000 years to reach the screening dose limit of 25 mrem/yr. The 10,000-year dose rate is entirely due to an assumed juvenile failure of one waste package; the first calculated waste package failure from corrosion was at about 100,000 years.

Defense in Depth—In addition to the natural barriers, EDA IIIa had four principal barriers (i.e., the Alloy-22 and SS-316L layers of the waste package, the fuel cladding, and the drip shield). Defense in depth for the first 10,000 years was estimated by computationally removing the waste package barriers. This simple neutralization estimate was repeated for several barriers included in the EDA. Based on these simple neutralization estimates for the engineered barriers, the design for EDA IIIa was given a rating of 3, which indicated its ability to mitigate the consequences of uncertainties in the individual barriers.

Uncertainties in Postclosure Performance—Within the first 10,000 years, there are significant uncertainties for the corrosion of Alloy-22 and the behavior of a repository in a high-temperature environment. There are significant uncertainties in the effects of thermal-hydrological-mechanical-chemical coupled process on seepage rate and fracture flow. High temperatures throughout the potential repository adversely affect the licensing factors (e.g., by creating the possibility that water would pool over this region and flow back into some of the drifts and onto the hot waste packages). The rating for the uncertainty in the first 10,000 years was 2.

Within the 10,000- to 100,000-year time frame, since there is no backfill, the performance of this design relies on the drip shield and waste package (the same as the uncertainties for the first 10,000 years). The rating for the 10,000- to 100,000-year time frame was 2.

Within the first million years, there are large irreducible uncertainties in long-term corrosion rates, long-term coupled processes, and natural system characteristics. The ability to predict over such a long time period is highly uncertain. Uncertainty also exists about whether there would be irreversible changes in the mountain (it is assumed that ambient conditions would return). The rating for the 100,000- to 1-million-year time frame was 1.

Engineering Acceptance—There were no unusual issues. The design is similar to the Viability Assessment design and the engineering issues for that design were considered carefully. The rating was 3.

Environmental Considerations—The LADS core team found no areas of significant environmental concern for this EDA. The rating was 3.

Construction, Operations, and Maintenance

Worker Safety—There were no unusual issues. The rating was 3.

Constructability—There were no unusual issues. The rating was 3.

Operations—No complex operations are anticipated (i.e., no aging, blending, or backfill). There could be some difficulty with the need to stage and sequence the cooler DOE waste packages so they can be interspersed with the hotter commercial spent nuclear fuel packages. This might be required to avoid creation of cool areas of individual drifts that might become sinks for water driven away from the hotter areas. The rating was 4.

Maintainability—There were no unusual issues. The rating was 3.

Handling Logistics—There were no unusual issues. The rating was 3.

Performance Confirmation—There were no unusual issues. The rating was 3.

Off-Normal Events—Blast cooling of a single drift to allow human access would require about 100 m³/s of ventilation for one week based on extrapolation from a similar design (CRWMS M&O 1995b). Portable shielding for radiation protection would consist of about 22 cm of steel and 11 cm of borated polyethylene (CRWMS M&O 1999jj).

Flexibility

Increased Capacity (If Authorized)— In order to accommodate 87,000 MTHM, this EDA could readily expand within the upper emplacement level, requiring about 1,000 acres. To accommodate 105,000 MTHM, this EDA could expand further into the characterized area, requiring about 1,200 acres (see Figure 5-1). The rating was 4.5.

Preclosure Period—Closure extended 100 to 300 years: No problems are anticipated. It could be beneficial to the ground support system if the relative humidity remained low (i.e., if moisture is removed by ventilation). The rating was 4.

Closure 10 years after emplacement ends: Because the cladding temperature goal would be exceeded if required to close 10 years early, it is unlikely that EDA IIIa could meet this requirement without significant modification. The rating was 2.

Change in Commercial Spent Nuclear Fuel Characteristics—Five-year-old commercial spent nuclear fuel arriving at the repository site late in the life of the repository would pose a problem for thermal management, particularly with respect to cladding temperature. The rating was 2.

Late Design Changes—Thermal design change (hot to cold): This EDA has area available for expanding the drift spacing. The modeling efforts to define the repository performance would be simplified by going to lower temperatures. The rating was 3.

Adding blending: Blending is not currently planned, but it would not be difficult to include. The rating was 3.

SUMMARY FOR EDA IIIb

Performance evaluations are based on the data presented in Figures 5-22 and 5-23.

Screening Criterion

The postclosure performance prediction of 0.017 mrem/yr is well below the 25 mrem/yr screening limit, for the screening period of 10,000 years.

Performance Demonstrability

Performance Margin—Based upon the predicted performance and screening limit, the performance margin ratio for EDA IIIb is 1,500. The peak dose rate is 100 mrem/yr at 520,000 years. It would take 310,000 years to reach the screening dose limit of 25 mrem/yr. The 10,000-year dose rate is entirely due to an assumed juvenile failure of one waste package; the first calculated waste package failure from corrosion was at about 150,000 years.

Defense in Depth—EDA IIIb had five principal barriers in addition to the natural barriers (i.e., three barriers in the waste package with dual corrosion-resistant materials and SS-316L, the fuel cladding, and the drip shield). Defense in depth for the first 10,000 years was estimated by computationally removing the waste package barriers. This simple neutralization estimate could be repeated for each of the other barriers included in the EDA. Based on the expected results of these simple neutralization estimates for the engineered barriers, the design for EDA IIIb was given a rating of 3, which indicates its ability to mitigate the consequences of uncertainties in the individual barriers.

Uncertainties in Postclosure Performance—Within the first 10,000 years, a dual corrosion-resistant, three-layer waste package would have excellent performance. However, the uncertainties in performance are increased by the uncertainties in the behavior of the waste package materials, particularly the material interactions (e.g., incompatibility of iron and titanium). The rating for the first 10,000 years was 2.5.

Within the first 100,000 years, since there is no backfill, the performance relies on the drip shield and waste package materials. This is also the reason for the uncertainties during the first 10,000 years. The rating for the uncertainties in the first 10,000- to 100,000-year time frame was 2.5.

Within the 100,000- to 1-million-year time frame, there are large irreducible uncertainties in long-term corrosion rates, long-term coupled processes, and natural system characteristics. The ability to predict over such a long time period is highly uncertain. Uncertainty also exists about whether there would be irreversible changes in the mountain (it is assumed that ambient hydrological conditions would return). The rating for uncertainties in this time frame was 1.

Engineering Acceptance—EDA IIIb is similar to the EDA IIIa design, except for the three-layer waste package. The fabrication plan involves a shrink-fit between the Alloy-22 outer shell and the Ti-7 middle layer, and a slip fit to the stainless steel. This type of fabrication is complex and there are few precedents. The process is less defensible. The rating was 2.5.

Environmental Considerations—The LADS core team found no areas of significant environmental concern for this EDA. The rating was 3.

Construction, Operations, and Maintenance

Worker Safety—There were no unusual issues. The rating was 3.

Constructability—There are possible problems with the two-layer/loose-shell construction of the waste package. The Alloy-22 to Ti-7 shrink fit and slip fit to stainless steel could require special processes, and more operation and inspection steps. The rating was 2.5.

Operations—No complex operations are anticipated (i.e., no aging, blending, or backfill). There could be some difficulty with the need to stage and sequence the cooler DOE waste packages so they can be interspersed with the hotter commercial spent nuclear fuel packages. This might be required to avoid creation of cool areas of individual drifts that might become sinks for water driven away from the hotter areas. The rating was 4.

Maintainability—There were no unusual issues. The rating was 3.

Handling Logistics—There were no unusual issues. The rating was 3.

Performance Confirmation—There were no unusual issues. The rating was 3.

Off-Normal Events—Blast cooling of a single drift to allow human access would require about 100 m³/s of ventilation for one week based on extrapolation from a similar design (CRWMS M&O 1995b). Portable shielding for radiation protection would consist of about 22 cm of steel and 11 cm of borated polyethylene (CRWMS M&O 1999jj).

Flexibility

Increased Capacity (If Authorized)—In order to accommodate 87,000 MTHM, this EDA could readily expand within the upper emplacement level, requiring about 1,000 acres. To accommodate 105,000 MTHM, this EDA could expand further into the characterized area, requiring about 1,200 acres (see Figure 5-1). The rating was 4.5.

Preclosure Period—Closure extended 100 to 300 years: No problems are anticipated. It could be beneficial to the ground support system if the relative humidity remained low (i.e., if moisture is removed by ventilation). The rating was 4.

Closure 10 years after emplacement ends: Because this EDA would exceed the cladding temperature goal if required to close 10 years early, it is unlikely that EDA IIIb could meet this requirement without significant modification. The rating was 2.

Change in Commercial Spent Nuclear Fuel Characteristics—Five-year-old commercial spent nuclear fuel arriving at the repository site late in the operational life of the repository would pose a problem for thermal management, particularly with respect to cladding temperature. The score was 2.

Late Design Changes—Thermal design change (hot to cold): This EDA has area available for expanding the drift spacing. The modeling efforts to define the repository performance would be simplified by going to lower temperatures. The rating was 3.

Adding blending: Blending is not currently planned, but it would not be difficult to include. The rating was 3.

5.3.3.2 Cost/Schedule

Cost/schedule estimates for EDAs IIIa and IIIb are presented in Table 5-7. These values are considered a rough order of magnitude (–25 percent to +50 percent) for conceptual design (CRWMS M&O 1999l, p. 14). See Section 5.3.7 for comparable Viability Assessment costs.

Table 5-7. Cost Estimates for Enhanced Design Alternatives IIIa and IIIb

Phase	Licensing Period (2002-2005) ¹	Construction Period (2005-2010) ¹	Operations Period (2010-2033) ¹				Monitoring Period (2033-2060) ¹	Closure Period (2060-2066) ¹			Total Cost
			Under-ground	Ventilation	Waste Package	Other		Drip Shield	Backfill	Other	
LCC											
IIIa)	\$0.8	\$3.0	\$1.9	\$0.4	\$4.1	\$4.3	\$1.6	\$3.3	NA	\$0.6	\$20.1
IIIb)	\$0.8	\$3.0	\$1.9	\$0.4	\$5.2	\$4.3	\$1.6	\$3.3	NA	\$0.6	\$21.3
NPV											
IIIa)	\$0.7	\$2.4	\$1.1	\$0.2	\$2.4	\$2.5	\$0.6	\$0.8	NA	\$0.1	\$10.7
IIIb)	\$0.7	\$2.4	\$1.1	\$0.2	\$3.0	\$2.5	\$0.6	\$0.8	NA	\$0.1	\$11.4

Key:

LCC: Repository life cycle cost in \$billion
¹Assumed dates

NPV: Net present value in \$billion

NA: Not applicable

5.3.4 Description of Enhanced Design Alternative IV

EDA IV is a shielded waste package design (CRWMS M&O 1999y) located entirely within the upper emplacement level (see Figures 5-1 and 5-24), with a high thermal load (85 MTHM/acre). About 740 acres are required, using only part of the upper emplacement level of the characterized area. The EDA IV waste package shell is 30-cm thick A516 steel (see Figure 5-25). Unlike the self-shielded waste package described in the DF on waste package self shielding (CRWMS M&O 1999k, p. iii), this design would not necessarily reduce worker exposure to radiation, but it would allow the extra radiation shields at the drift entrances to be eliminated. The only requirements necessary to allow human access to the emplacement drifts for off-normal events would be blast cooling (100 m³/s ventilation) to reduce the temperature in the drifts and the placement of portable neutron shields (5-cm-thick borated polyethylene) over the waste packages. The EDA IV waste package also has an integral filler, which acts as a sponge for oxygen (O-depletion), that is more extensive than in the other EDA designs (see Figure 5-26). For emplacement, the waste packages are line loaded with 10 cm of separation. The drift spacing is 56 m between the centerlines.

The goals of EDA IV were to keep the gamma dose from the waste package below 200 mrem/hr, keep the fuel cladding temperature below 350°C, and keep the emplacement drifts dry for

thousands of years. Continuous ventilation at the rate of 2 to 10 m³/s in the emplacement drifts would be required for the 50-year preclosure period.

The EDA IV waste package weighs 22 metric tons more than those used with the other EDAs. Since this waste package requires a hot, dry postclosure environment to be successful, it is necessary to include backfill at closure. Because of this necessity for high heat, there is a possibility that the maximum temperature for the fuel cladding would be exceeded for some waste packages.

The EDA IV waste packages had temperature and humidity histories that entered the carbon steel corrosion window of susceptibility, defined as temperatures below 125°C while relative humidity is above approximately 60 percent (see Figures 5-27 and 5-28). The performance assessment calculations (thermal, waste package failure, and dose rate) were based on no aging and 50 years of ventilation with 50 percent of the waste thermal power being removed during the ventilation period.

5.3.4.1 Enhanced Design Alternative IV Evaluation Summary

A summary of the evaluation of EDA IV, based on the criteria described in Section 5.2, is provided below. The postclosure performance predictions presented under "Screening Criterion" and "Performance Demonstrability" are based on the data presented in Figures 5-29 and 5-30, and were derived from the calculations contained in the performance assessment calculations (CRWMS M&O 1999kk).

Screening Criterion

The postclosure performance prediction of 0.00014 mrem/yr is well below the 25 mrem/yr screening limit, for the screening period of 10,000 years.

Performance Demonstrability

Performance Margin—Based upon the predicted performance and screening limit, the performance margin ratio for EDA IV is 180,000. The peak dose rate is 1,200 mrem/yr at 320,000 years. It would take approximately 100,000 years to reach the screening dose limit of 25 mrem/yr. The 10,000-year dose rate is entirely due to an assumed juvenile failure of one waste package; the first calculated waste package failure from corrosion was at about 15,000 years.

Defense in Depth—EDA IV had four principal barriers in addition to the natural barriers; the fuel cladding and the drip shield constitute two of these barriers. The backfill and the waste package have a common-mode failure with humid air corrosion, but it would take more than 1,000 years for the steel to degrade, so both are counted as principal barriers. Defense in depth for the first 10,000 years was estimated by computationally removing the waste package barriers. This simple neutralization estimate could be repeated for each of the other barriers included in the EDA. Based on the expected results of these simple neutralization estimates for the engineered barriers, the design for EDA IV was given a rating of 2, which indicates its inability to mitigate the consequences of uncertainties in the individual barriers.

Uncertainties in Postclosure Performance—Within the first 10,000 years, the uncertainties in postclosure performance are related to the strong necessity that the backfill properly control the temperature and relative humidity conditions to protect the drip shield. If this system does not operate properly, the carbon steel waste packages will fail much earlier than the waste packages in the other EDAs. In addition, high temperatures throughout the potential repository would adversely affect licensing factors (e.g., by creating the possibility that water could pool over this region and flow back into some of the drifts and onto the hot waste packages). The rating for the first 10,000 years was 1.5.

Within the 10,000- to 100,000-year time frame, the waste packages start to fail between 15,000 and 35,000 years. If the backfill does not perform as expected, the thermal conditions would change and the drip shield would fail sooner. The rating for the uncertainty in the 10,000 to 100,000 year time frame was 1.5.

Within the 100,000- to 1-million-year time frame, there is large irreducible uncertainty in long-term coupled processes and natural system characteristics. The ability to predict over such a long time period is highly uncertain. Uncertainty also exists about whether there would be irreversible changes in the mountain (it is assumed that ambient conditions would return). The rating for this time frame was 1.

Engineering Acceptance—The carbon steel used to construct the waste package is very thick (30 cm). Large amounts of welding (using robotics in a hot cell) would be required, and there is an increased probability of weld defects. The necessary welding techniques are well accepted, but the technology of a 30-cm-thick closure weld would require development. The use of backfill in controlling relative humidity and temperature may be difficult to defend and poorly accepted when it is integral to the case for regulatory performance. There are no precedents for the emplacement of very heavy packages in a hot, radioactive environment. The rating was 2.

Environmental Considerations—The LADS core team found no areas of significant environmental concern for this EDA. The rating was 4.

Construction, Operations, and Maintenance

Worker Safety—There were no unusual issues. The score was 3.

Constructability—The closure welds on the very thick-walled waste package would be difficult to perform and inspect, and the necessary support equipment would be heavier. Backfill emplacement may be difficult. The rating was 2.

Operations—Much heavier waste packages could lead to operational complications. Emplacement of the backfill could present difficulties. In this EDA, there is more reliance on the waste package sequencing within the emplacement drifts than in the other EDAs. The rating was 2.

Maintainability—There were no unusual issues. The rating was 3.

Handling Logistics—The weight of the waste package is at least 22 metric tons more than the other EDAs. The rating was 2.

Performance Confirmation—There were no unusual issues. The rating was 3.

Off-Normal Events—Blast cooling of a single drift to allow human access would require about 100 m³/s of ventilation for one week (CRWMS M&O 1995b). Portable shielding for radiation protection would consist of only about 9 cm of borated polyethylene (CRWMS M&O 1999jj).

Flexibility

Increased Capacity (If Authorized)— In order to accommodate 87,000 MTHM, this EDA could readily expand within the upper emplacement level, requiring about 1,000 acres. To accommodate 105,000 MTHM, this EDA could expand further into the characterized area, requiring about 1,200 acres (see Figure 5-1). The rating was 4.5.

Preclosure Period—Closure extended 100 to 300 years: No problems are anticipated. Ventilation is advantageous for the ground support because it helps lower the relative humidity. The rating was 4.

Closure 10 years after emplacement ends: Because the cladding temperature goal could be exceeded for some waste packages, it is unlikely that EDA IV could meet this requirement without significant modification. Backfill would exacerbate this problem. The rating was 1.

Change in Commercial Spent Nuclear Fuel Characteristics—Five-year-old commercial spent nuclear fuel arriving at the repository site late in the life of the repository would pose a problem for thermal management, particularly with respect to cladding temperature. The rating was 2.

Late Design Changes—Thermal design change (hot to cold): This EDA is not suitable for a low-temperature design because the waste package would not be suitable for a cool, moist environment. In this EDA, high heat would be needed to drive off moisture and thereby delay the degradation of the waste package. The rating was 1.

Adding blending: There would be no special problems with adding blending to this EDA. The rating was 3.

5.3.4.2 Cost/Schedule

The cost/schedule estimate for EDA IV is presented in Table 5-8. These values are a rough order of magnitude (–25 percent to +50 percent) for conceptual design (CRWMS M&O 1999ll, p. 14). See Section 5.3.7 for comparable Viability Assessment design costs.

Table 5-8. Cost Estimate for Enhanced Design Alternative IV

Phase	Licensing Period (2002-2005) ¹	Construction Period (2005-2010) ¹	Operations Period (2010-2033) ¹				Monitoring Period (2033-2060) ¹	Closure Period (2060-2066) ¹			Total Cost
			Under-ground	Ventilation	Waste Package	Other		Drip Shield	Backfill	Other	
LCC	\$0.8	\$3.2	\$1.9	\$0.4	\$4.3	\$4.3	\$1.6	\$4.3	\$0.4	\$0.5	\$21.7
NPV	\$0.7	\$2.5	\$1.1	\$0.2	\$2.5	\$2.5	\$0.6	\$1.1	\$0.1	\$0.1	\$11.3

Key:

LCC: Repository life cycle cost in \$billion NPV: Net present value in \$billion

¹Assumed dates**5.3.5 Description of Enhanced Design Alternative V**

EDA V is a very high thermal loading design (150 MTHM/acre) (CRWMS M&O 1999z). It covers the smallest area of the five EDAs, 420 acres in the lower emplacement level (see Figures 5-1 and 5-31). The purpose of considering a very high thermal loading design was to provide a hot, dry drift environment for thousands of years and avoid extended periods of warm, moist conditions. The emplacement drifts would be surrounded by rock at temperatures above the boiling point of water (temperatures greater than 96°C, the boiling point of water at the repository altitude). The high, relatively uniform drift temperature would drive moisture away from the drift. The benefits would be a lower relative humidity and a reduction in the possibility of water seepage into the drift for a very long time.

The goals of EDA V were to have drift wall temperatures less than 225°C to maintain rock stability, a waste package cladding temperature less than 350°C, and to keep the drift dry for several thousand years. The rationale for allowing a higher drift wall temperature was to maximize the potential benefit of mountain-scale heating while minimizing the constraints on local temperatures. For the drift wall limit, the increase in rock thermal expansion coefficient becomes steeper at about 225°C. Modeling showed, however, that this design had large margins on the two temperature constraints but did not keep the drifts dry as long as had been expected. Whether the temperature of the waste package would drop below 80°C before the relative humidity increased to 80 percent is uncertain.

In this EDA, the waste would require blending to within 20 percent of the average waste package heat output. The waste would be specifically sorted according to type, heat output, and age, and then loaded into packages with similarly selected waste to control the heat output of each waste package. The waste packages are 2 cm of Alloy-22 over 5 cm of SS-316L, and would be line loaded with a 10 cm spacing between waste packages. Drift spacing would be 32.4 m. Preclosure ventilation (2 to 10 m³/s) would reduce the air and drift temperatures as well as remove moisture from the drifts. Ti-7 drip shields would be put in place at the time of closure.

A major advantage of this EDA is that it is located entirely within the lower emplacement level of the repository. The lower emplacement level is 73 m lower in elevation and the rate of water percolation is half that in the upper emplacement level. Because the postclosure temperature would be above 96°C, there would be no water seepage during the thermal pulse. Calculations show, however, that the period of high heat would not be as long as desired. Access to the lower

emplacement level requires a third access tunnel due to the longer vertical transit distance involved.

A disadvantage of EDA V is that the postclosure conditions could lead to localized corrosion and failure of about 4 percent of the waste packages during the 10,000- to 100,000-year period. Further optimization could have produced longer dry out, while not exceeding the drift wall and cladding temperature constraints; this may have reduced the waste package localized corrosion failures.

As part of the analysis of this EDA, two loss of ventilation accidents were considered, using the ANSYS computer code. The first assumed no ventilation for a period of one year, beginning 40 years after waste receipt (15 years after emplacement) since EDA V, at that time, included 25 years of aging. The results were that the drift wall temperature increased to 120°C, but returned to 65°C soon after the 10 m³/s ventilation rate was restored. The second loss of ventilation accident calculation assumed no ventilation for a period of one month, beginning 20 years after the first situation. The drift wall temperature increased to about 95°C, and again returned to about 65°C soon after the 10 m³/s ventilation rate was restored. Thus, it was concluded that a ventilated repository is quite robust, thermally, to a relatively extended period of lost ventilation capacity due to a power outage or rockfall in a main ventilation drift, ramp, or shaft (CRWMS M&O 1999z).

For EDA V, all the waste packages had temperature and humidity histories that entered the Alloy-22 crevice corrosion window of susceptibility, defined as temperatures between 85 and 125°C while relative humidity is above 80 percent (see Figures 5-32 and 5-33). The performance assessment calculations (thermal, waste package failure, and dose rate) were based on 25 years of aging and 75 years of ventilation with 50 percent of the waste thermal power being removed during the ventilation period. The consequence of the aggressive conditions was the initial waste package failure at about 9,500 years and about 4 percent of the waste packages failing by crevice corrosion by 100,000 years. However, the releases from these packages were relatively minor because the breaches were small and did not allow much water to enter the waste package.

5.3.5.1 Enhanced Design Alternative V Evaluation Summary

A summary of the evaluation of EDA V, based on the criteria described in Section 5.2, is provided below. The postclosure performance predictions presented under "Screening Criterion" and "Performance Demonstrability" are based on Figures 5-34 and 5-35, and were derived from the calculations contained in the performance assessment calculations (CRWMS M&O 1999kk).

Screening Criterion

The postclosure performance prediction of 0.02 mrem/yr is well below the 25 mrem/yr screening limit, for the screening period of 10,000 years.

Performance Demonstrability

Performance Margin—Based upon the predicted performance and screening limit, the performance margin ratio for EDA V is 1,250. The peak dose rate is 200 mrem/yr at 720,000 years. It would take 300,000 years to reach the screening dose limit of 25 mrem/yr. The 10,000-year dose rate is entirely due to an assumed juvenile failure of one waste package. The first calculated waste package failure from corrosion was at about 9,500 years; however, there was not adequate time for releases through localized corrosion failures to reach the accessible environment by 10,000 years.

Defense in Depth—In addition to the natural barriers, EDA V has four principal barriers (i.e., the Alloy-22 and SS-316L layers of the waste package, the fuel cladding, and the drip shield). Defense in depth for the first 10,000 years was estimated by computationally removing the waste package barriers. This simple neutralization estimate could be repeated for each of the other barriers included in the EDA. Based on the expected results of these simple neutralization estimates for the engineered barriers, the design for EDA V was given a rating of 3, which indicates its ability to mitigate the consequences of uncertainties in the individual barriers.

Uncertainties in Postclosure Performance—Within the first 10,000 years, parts of the repository environment could have aggressive conditions (high temperature and high relative humidity) for a relatively long period of time. Thus, uncertainties in the behavior of the engineered barriers during this time are significant. Localized corrosion is anticipated on some waste packages in the aggressive environment, which introduces other uncertainties. The rating for the uncertainty in the first 10,000 years was 2.

Within the 10,000- to 100,000-year time frame, since there is no backfill, the performance relies on the drip shield and waste package. An extended period of corrosive conditions was not avoided, leading to failure of about 4 percent of the waste packages between 10,000 and 100,000 years. The rating for the uncertainties in this time frame was 2.

Within the 100,000- to 1-million-year time frame, there are large irreducible uncertainties in long-term corrosion rates, long-term coupled processes, and natural system characteristics. The ability to predict over such a long time period is highly uncertain. Uncertainty also exists about whether there would be irreversible changes in the mountain (it is assumed that ambient hydrological conditions would return). The rating for this time frame was 1.

Engineering Acceptance—It would be difficult to demonstrate the postclosure function of water being driven off for the length of time anticipated and needed (heating rock to boil water and maintain low relative humidity). The relatively long period with hot/moist conditions is associated with an increased time with localized corrosion. This could lead to earlier failure of the drip shields than has been predicted. The rating was 1.5.

Environmental Considerations—The LADS core team found no areas of significant environmental concern for this EDA. The rating was 3.

Construction, Operations, and Maintenance

Worker Safety—This EDA has the smallest repository area and least drifting. The rating was 3.5.

Constructability—There were no unusual issues. The rating was 3.

Operations—Blending would be required. The rating was 3.

Maintainability—There were no unusual issues. The rating was 3.

Handling Logistics—There were no unusual issues. The rating was 3.

Performance Confirmation—There were no unusual issues. The rating was 3.

Off-Normal Events—Blast cooling of a single drift to allow human access would require about 100 m³/s of ventilation for one week based on extrapolation from a similar design (CRWMS M&O 1995b). Portable shielding for radiation protection would consist of about 19 cm of steel and 10 cm of borated polyethylene (CRWMS M&O 1999jj).

Flexibility

Increased Capacity (If Authorized)— In order to accommodate 87,000 MTHM, this EDA could readily expand within the lower emplacement level, requiring about 600 acres. To accommodate 105,000 MTHM, this EDA could expand further into the characterized area, requiring about 700 acres (see Figure 5-1). The rating was 5.

Preclosure Period—Closure extended 100 to 300 years: This can easily be accommodated. The rating was 4.

Closure 10 years after emplacement ends: There are potential problems with maintaining the cladding temperature goal. It is unlikely that EDA V could meet this requirement without significant modification. The rating was 2.

Change in Commercial Spent Nuclear Fuel Characteristics—Five-year-old commercial spent nuclear fuel arriving at the operational repository site late in the life of the repository would pose a problem for thermal management, particularly with respect to cladding temperature. The rating was 2.

Late Design Changes—Thermal design change (hot to cold): The layout and the design would change, but some of the analyses could be simplified by going to lower temperatures. The rating was 3.

Eliminating Blending: Blending is an integral part of EDA V. The elimination of blending would require the use of other thermal management tools, such as package derating, aging, or lower thermal load. The rating was 2.

5.3.5.2 Cost/Schedule

The cost/schedule estimate for EDA V is presented in Table 5-9. All of these values are a rough order of magnitude (–25 percent to +50 percent) for conceptual design (CRWMS M&O 1999II, p. 15). See Section 5.3.7 for comparable Viability Assessment design costs.

Table 5-9. Cost Estimate for Enhanced Design Alternative V

Phase	Licensing Period (2002-2005) ¹	Construction Period (2005-2010) ¹	Operations Period (2010-2033) ¹				Monitoring Period (2033-2060) ¹	Closure Period (2060-2066) ¹			Total Cost
	All	All	Under-ground	Ventilation	Waste Package	Other	All	Drip Shield	Backfill	Other	
LCC	\$0.8	\$3.1	\$1.9	\$0.3	\$4.0	\$4.5	\$1.6	\$3.2	NA	\$0.5	\$20.0
NPV	\$0.7	\$2.5	\$1.1	\$0.2	\$2.3	\$2.6	\$0.6	\$0.8	NA	\$0.1	\$10.8

Key:

LCC: Repository life cycle cost in \$billion
¹Assumed dates

NPV: Net present value in \$billion

NA: Not applicable

5.3.6 General Observations From the Evaluation of Enhanced Design Alternatives

The calculated dose rates, temperatures, and humidities for the EDAs were presented in Sections 5.3.1, 5.3.2, 5.3.3, 5.3.4, and 5.3.5. In the performance assessment calculations, the temperatures and humidities are used as inputs into probabilistic drip shield and waste package lifetime calculations. In turn, those results and site property inputs are used to calculate (deterministically, for the LADS analyses) the radionuclide mobilization, transport, and consequent dose rates at the accessible environment. Figures 5-36 and 5-37 (CRWMS M&O 1999kk) summarize the calculated drip shield and waste package failure distributions for the fraction of the waste packages that are seeped upon (about 28 percent for the Viability Assessment and EDAs III through IV, 25 percent for EDA I, 27 percent for EDA II, and 11 percent for EDA V [CRWMS M&O 1999kk]; the long-term average climate seepage depends on the percolation flux which depends on the footprint). For waste packages that do not experience seeps, there are very few failures, even in one million years (DOE 1998b, Vol. 3, Figure 3-48).

General observations include:

- All of the EDAs performed very well relative to the 25 mrem/yr screening criterion. All had calculated peak dose rates in the expected 10,000-year regulatory period of at least a factor of 1,200 lower than the 25 mrem/yr screening criterion, and none reached that level before approximately 100,000 years.
- A Ti-7 drip shield appears to be able to protect the waste packages from dripping water for thousands of years, allowing the temperature of the waste packages to fall below the level of localized corrosion vulnerability before they could be contacted by dripping water.
- The waste package design used in most EDAs (corrosion-resistant Alloy-22 over stainless steel) appears capable of achieving a minimum life of 100,000 years, when

protected by drip shields, in the anticipated environment in the potential repository at Yucca Mountain.

- Lower temperatures reduce uncertainties in localized corrosion, rock, alteration, and coupled processes in the natural system, thereby improving factors affecting licensability.
- Higher temperatures allow use of larger capacity waste packages and shorter total emplacement drift length that must be excavated. This reduces the probability of industrial accidents during construction and operation, and reduces net costs.
- Higher areal mass loading provides more flexibility with respect to the location of the potential repository within the characterized area, the ability to adapt to the discovery of regions that should be avoided, and the ability to increase capacity.

5.3.7 Viability Assessment Design Cost Comparison

Cost estimates for the Viability Assessment design are provided in Table 5-10 for the purpose of comparing the cost estimates for the EDA conceptual designs with cost estimates prepared for the Viability Assessment design (CRWMS M&O 1999II, p. 15).

Table 5-10. Cost Estimate for the Viability Assessment Design

Phase	Licensing Period (2002-2005) ¹	Construction Period (2005-2010) ¹	Operations Period (2010-2033) ¹				Monitoring Period (2033-2060) ¹	Closure Period (2060-2066) ¹			Total Cost
			Under-ground	Ventilation	Waste Package	Other		Drip Shield	Backfill	Other	
System	All	All					All				
LCC	\$0.8	\$2.9	\$2.6	NA	\$3.9	\$4.7	\$1.6	NA	NA	\$0.4	\$16.8 ²
NPV	\$0.7	\$2.3	\$1.5	NA	\$2.3	\$2.6	\$0.5	NA	NA	\$0.1	\$10.1

Key:

LCC: Repository life cycle cost in \$billion

NPV: Net present value in \$billion

NA: Not applicable

¹Assumed dates

²The Viability Assessment design cost estimate (DOE 1998b, Vol. 5) was based on closure at 100 years and had an estimate of \$18 billion. For comparison reasons, the amounts shown in this table are based on a 50-year closure.

Figure 5-1. Location of Upper and Lower Emplacement Levels within the Principal Rock Stratigraphic Units at Yucca Mountain

Figure 5-2. Waste Package for Enhanced Design Alternative I

Figure 5-3. Drip Shield Over Waste Package

Figure 5-4. Enhanced Design Alternative I Layout

EDA-I T/RH Waste Package Trajectories

Figure 5-5. Temperature and Relative Humidity Histories for Representative Waste Packages Used in the Corrosion Calculations for Enhanced Design Alternative I
Each history line shows the progress of the thermal conditions as time proceeds. The window of susceptibility is the temperature/humidity range that may initiate crevice corrosion of Alloy-22.

EDA I - Waste Package Temperatures The Window of Susceptibility is Not Entered by Any WPs

Figure 5-6. Temperature Histories for Two Representative Waste Packages in Enhanced Design Alternative I
The window of susceptibility begins when humidity returns to 80 percent; thus, a different window is shown for each of the two waste packages.

Figure 5-7. Enhanced Design Alternative I 10,000 Year Total Dose Rate History

Figure 5-8. Enhanced Design Alternative I One Million Year Total Dose Rate History

Figure 5-9. Enhanced Design Alternative II Layout

Figure 5-10. Extent of Boiling Fronts for Enhanced Design Alternative II (drip shields and backfill removed for clarity)

**EDA II (Backfill, No aging) - Waste Package Trajectories
Base case infiltration LTA**

Figure 5-11. Temperature and Relative Humidity Histories for Representative Waste Packages Used in the Corrosion Calculations for Enhanced Design Alternative II (Without Aging)
Each history line shows the progress of the thermal conditions as time proceeds. The window of susceptibility is the temperature/humidity range that may initiate crevice corrosion of Alloy-22.

**EDA II (Backfill, No aging) - Waste Package Temperatures
The Window of Susceptibility is not Entered by any WPs**

Figure 5-12. Temperature Histories for Two Representative Waste Packages in Enhanced Design Alternative II (Without Aging)
The window of susceptibility begins at the time when humidity returns to 80 percent; thus, a different window is shown for each of the two waste packages.

Figure 5-13. Enhanced Design Alternative II 10,000 Year Total Dose Rate History

Figure 5-14. Enhanced Design Alternative II One Million Year Total Dose Rate History

Figure 5-15. Waste Package for Enhanced Design Alternative IIIb

Figure 5-16. Enhanced Design Alternative III Layout

Figure 5-17. Line-Loading for Enhanced Design Alternative III

Figure 5-18. Temperature and Relative Humidity Histories for Representative Waste Packages Used in the Corrosion Calculations for Enhanced Design Alternative III
Each history line shows the progress of the thermal conditions as time proceeds. The window of susceptibility is the temperature/humidity range that may initiate crevice corrosion of Alloy-22.

EDA III - Waste Package Temperatures The Window of Susceptibility is Entered by Most WPs

Figure 5-19. Temperature Histories for Two Representative Waste Packages in Enhanced Design Alternative III
The window of susceptibility begins when humidity returns to 80 percent; thus, a different window is shown for each of the two waste packages.

EDA IIIa 10,000-yr Total Dose-Rate History All Pathways, 20 km

Figure 5-20. Enhanced Design Alternative IIIa 10,000 Year Total Dose Rate History

Figure 5-21. Enhanced Design Alternative IIIa One Million Year Total Dose Rate History

Figure 5-22. Enhanced Design Alternative IIIb 10,000 Year Total Dose Rate History

Figure 5-23. Enhanced Design Alternative IIIb One Million Year Total Dose Rate History

Figure 5-24. Enhanced Design Alternative IV Layout

Figure 5-25. Waste Package for Enhanced Design Alternative IV

Integral Filler

Figure 5-26. Integral Filler in Waste Package

EDA IV T/RH Waste Package Trajectories

Figure 5-27. Temperature and Relative Humidity Histories for Representative Waste Packages Used in the Corrosion Calculations for Enhanced Design Alternative IV
Each history line shows the progress of the thermal conditions as time proceeds. The window of susceptibility is the temperature/humidity range that allows corrosion of carbon steel. The first waste package failure was at about 15,000 years due to these temperature/humidity conditions.

EDA IV - Waste Package Temperatures The Window of Susceptibility is Entered by All WPs

Figure 5-28. Temperature Histories for Two Representative Waste Packages in Enhanced Design Alternative IV
The window of susceptibility begins at the time when humidity returns to 60 percent; thus, a different window is shown for each of the two waste packages.

Figure 5-29. Enhanced Design Alternative IV 10,000 Year Total Dose Rate History

Figure 5-30. Enhanced Design Alternative IV One Million Year Total Dose Rate History

Figure 5-31. Enhanced Design Alternative V Layout

EDA V T/RH Waste Package Trajectories

Figure 5-32. Temperature and Relative Humidity Histories for Representative Waste Packages Used in the Corrosion Calculations for Enhanced Design Alternative V
Each history line shows the progress of the thermal conditions as time proceeds. The window of susceptibility is the temperature/humidity range that may initiate crevice corrosion of Alloy-22.

EDA V - Waste Package Temperatures
The Window of Susceptibility is Entered by All WPs

Figure 5-33. Temperature Histories for Two Representative Waste Packages in Enhanced Design Alternative V
 The window of susceptibility begins when humidity returns to 80 percent; thus, a different window is shown for each of the two waste packages.

EDA V
10,000-yr Total Dose-Rate History
All Pathways, 20 km

Figure 5-34. Enhanced Design Alternative V 10,000 Year Total Dose Rate History

Figure 5-35. Enhanced Design Alternative V One Million Year Total Dose Rate History

Figure 5-36. Drip Shield Failure Distribution for Those Drip Shields that Experience Seeps

Figure 5-37. Waste Package Failure Distribution for Those Waste Packages that Experience Seeps

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6. COMPARATIVE EVALUATION OF ENHANCED DESIGN ALTERNATIVES

Near the end of Phase II, five enhanced design alternatives (EDAs) were evaluated individually according to the common set of Phase II evaluation criteria. The individual EDA evaluations and the technical bases for the evaluations are provided in the discussions of each EDA in Section 5.3. These EDAs were then compared and ranked on the basis of the comparisons, which are described in this section. The methods used to compare and rank the EDAs are described in Section 6.1, below. The results of the comparative evaluation, the ranking process, and the final design recommendation are provided in Sections 6.2, 6.3, and 6.4, respectively. Section 6.5 represents a comparison between the recommended design, EDA II, and the Viability Assessment design.

6.1 ENHANCED DESIGN ALTERNATIVE COMPARATIVE EVALUATION METHODS

Phase II evaluation criteria (Section 5.2) were developed by the License Application Design Selection (LADS) core team, endorsed by the License Application Design Integration Group, and distributed to the EDA lead design engineers early in the process of design development. The purpose was to inform the EDA leads of the criteria against which the EDAs would ultimately be evaluated. In addition, a lead individual was assigned to each evaluation criterion (a criterion lead), who was responsible for the consistent definition of each criterion.

The five EDAs were rated according to the Phase II evaluation criteria in a four-day series of core team meetings near the end of Phase II. In the meetings, each EDA was described by the EDA lead and the core team lead for the EDA. Discussion included the design development that had occurred, the design trades that had been made to attain the temperature goals for each EDA, and the design trades or other refinements that could be made in the future if the design were carried forward. Criterion leads provided insights to the evaluation criteria ratings. Following the general meeting, the core team discussed each EDA, reviewed calculations and design analyses for the quantitative evaluation criteria (e.g., performance assessment), and assigned evaluation criteria ratings. These criteria ratings were presented and discussed by the core team leads during the Phase II workshop. EDA ranking and design recommendation meetings were held following the workshop.

EDA Evaluation Workshop

A two-day EDA Evaluation Workshop to review the EDAs was convened on March 8 and 9, 1999. The workshop was attended by observers from the U.S. Department of Energy (DOE), the Nuclear Waste Technical Review Board, the U.S. Nuclear Regulatory Commission, the Design Alternatives Review Panel, the Repository Consulting Board, and other groups.

The meeting commenced with an overview of the LADS process and the activities conducted during Phase II. (Phase II began immediately after the 10-day Phase I workshop was completed.) The EDA lead design engineers summarized the temperature goals associated with each EDA, the design development that had been conducted to reach the goals, and the design trades that could be made in the future to refine and optimize the design. Following each design description, a representative from the performance assessment group described the assumptions

used in the performance assessment modeling, the temperature and relative humidity calculation results, and the dose rates calculated for the 10,000- and 1-million-year time periods. This was followed by a presentation by the core team lead for each EDA, who described the evaluation criteria ratings. After each of the five EDAs had been discussed, the cost estimates were presented, both in terms of repository life cycle costs in 1998 dollars and net present value costs, taking into account the timing of costs over the entire preclosure period.

Discussions throughout the workshop, and comments made by observers at the end of the workshop, helped to define the advantages and disadvantages of the various EDAs.

EDA Ranking Meeting

The EDAs were ranked relative to each evaluation criterion in a one-day meeting on March 10, 1999, attended by the LADS core team and a number of observers. To develop an overall ranking, the team systematically compared each EDA to the other EDAs taken one at a time, a process known as "pair-wise comparison." For each pair-wise comparison, the team was asked to decide which of the two EDAs would be selected based only on consideration of relative performance on the single criterion being considered, without reference to performance on any of the other criteria. The results of these pair-wise comparisons were then used to deduce the rank ordering of the five EDAs with respect to the criterion being considered, as described further below.

For each pair-wise comparison, the team began by considering the evaluations of the two EDAs according to the subcriteria of the criterion in question. The team examined the scores assigned to each EDA for each subcriterion, and, more importantly, the reasons that justified those scores, documented in Section 5.3. The ranking of the two EDAs was not based simply on an aggregation of the subcriteria evaluations, for several reasons. First, the team had information to work with in addition to the evaluations of the EDAs considered separately. This additional information included the insights about the different criteria gained over the course of those evaluations, additional analyses that became available after the evaluations were completed, and discussions of those evaluations during a two-day EDA evaluation workshop held immediately before the rating took place. The fact that two EDAs might have received identical scores on a particular subcriterion when the EDAs were evaluated separately did not imply that the team would conclude that they were indistinguishable on that subcriterion when the EDAs were compared in the light of all of the information just described. Second, the available information for the subcriteria did not lend itself to any sort of quantitative aggregation to determine the ranking for the criterion. For some subcriteria, the available quantitative measures had incommensurable units (e.g., millirem/year and numbers of barriers). In the case of the numerical scores on the constructed scales used for some subcriteria, the scales were not developed in a way that would allow meaningful mathematical combination and manipulation.

In conducting the pair-wise comparisons, the team integrated all of the available information to reach a judgment about which EDA would be selected if the only relevant criterion were the one being considered. Team members first stated their initial judgments about which EDA should rank higher, and the reasons for those judgments. Differences among the team members were discussed until a consensus was reached about the appropriate relative ranking of the two EDAs,

and the important reasons for that ranking. During this process, the team discussed the relative importance of the various subcriteria, but no explicit weighting process was used.

Once all of the pair-wise comparisons were completed for a particular criterion, the team determined the overall rank ordering of all of the EDAs by inspection of the pair-wise rankings. No judgment was involved at this step, since the overall rank ordering is logically implied by the results of the pair-wise rankings. For example, if EDA I were ranked higher than both EDA II and EDA III, and EDA III were ranked higher than EDA II, then the rank ordering of the three EDAs would be EDA I, EDA III, EDA II. While it is theoretically possible that such a process could fail to provide a unique rank ordering, that complication did not arise in this case.

6.2 ENHANCED DESIGN ALTERNATIVE RANKING

This section summarizes the assessments of EDAs to place them in rank order for each evaluation criterion. The technical bases for the ratings of each EDA individually are discussed in detail in Section 5.3 and detailed design descriptions are reported in the associated references. As discussed in Section 5.3, the quantitative scales (e.g., performance in millirem/year) and constructed scales (e.g., 1 to 5) are not designed to allow meaningful mathematical combinations in a quantitative decision methodology. Because the scores do not have a numerical meaning, mathematical combinations are also meaningless. Rather, they provided guides to help the LADS core team perform consistent evaluations on the various EDAs when they were considered separately. The fundamental process for comparative evaluation of the EDAs was direct ranking of the EDAs with reference to each evaluation criterion, using a pair-wise comparison process as discussed above.

In ranking the EDAs, subcriteria that received identical scores across all of the EDAs were generally considered to be nondiscriminating. Only those criteria that were judged to discriminate between the EDAs are discussed here. No explicit weights were used for subcriteria considered as discriminators; nonetheless, some were judged to be of greater importance than others; therefore, equal weights should not be assumed. The discussion below summarizes the technical bases for the ranking of the EDAs for the four principal evaluation criteria. First, the subcriteria that discriminate among the designs are identified, followed by the technical bases for the rankings.

6.2.1 Enhanced Design Alternative Ranking for Performance Demonstrability Criterion

The peak dose rate was used to confirm that the performance of the EDAs would meet the screening criterion of 25 mrem/yr within 10,000 years. All of the EDAs had calculated 10,000-year dose rates that lie well below 25 mrem/yr. The 10,000-year dose rates are entirely due to an assumed juvenile failure of one waste package. Because all of the EDAs showed excellent performance and performance margin, the assessment of performance demonstrability was based on consideration of the degree of defense in depth, engineering acceptance, and uncertainties in postclosure performance.

Design Discriminators

Based on the range of ratings across the EDAs, there were two principal discriminators for this criterion: 1) the uncertainty in the 10,000-year postclosure performance, and 2) engineering

acceptance. The uncertainty in the 100,000-year postclosure performance was a secondary discriminator. Defense-in-depth factors (number of defense-in-depth barriers and 10,000-year neutralization evaluation) were also secondary discriminators. However, the confidence in this factor was assessed to be low because full neutralization calculations for 10,000- and 1-million-year performance had not been performed. Defense-in-depth barriers for each EDA are discussed in Section 5.3.

The uncertainty in the 1-million-year postclosure performance was a nondiscriminator because all of the EDAs were assigned a rating of 1 for this factor. The ability to predict over such a long time period was judged to be highly uncertain. It was judged that there are large, irreducible uncertainties in the behavior of the natural system (e.g., amount of seepage) and in the degradation rates of the engineered barrier system materials (including the waste form) in the several-hundred-thousand-year time frame. For designs that had high temperatures over a long time period, added uncertainties existed regarding possible irreversible changes in the thermal-hydrologic-mechanical-chemical properties of Yucca Mountain. Preclosure environmental considerations were also a nondiscriminator.

EDA Ranking

EDA I had the highest ranking for the performance demonstrability criterion because the uncertainty in the 10,000-year postclosure performance of the EDA was relatively low, and the engineering acceptance was relatively high. The uncertainties in postclosure performance in 10,000 years were reduced in the design by avoiding significant modification of the surrounding rock (e.g., coupled thermal-hydrologic processes were minimized). Assuming that relative humidities would be high due to the cooler temperatures, the time in an aggressive corrosion regime for the waste package (temperature greater than 85°C) was relatively short (a few hundred years). The need for models that reflect coupled processes, localized corrosion mechanisms, and other complex mechanisms was significantly reduced for this EDA. For engineering acceptance, EDA I had a relatively high rating because it would be easier to demonstrate postclosure function (e.g., resulting from less heat and a shorter time in corrosive regimes). In addition, all elements of the design had engineering precedents.

EDA I was also evaluated more favorably for 100,000-year performance uncertainty. No waste package failure was predicted during the 10,000- to 100,000-year time period. Postclosure performance is not strongly influenced by the timing of temperature and relative humidity peaks, and fewer corrosion issues were anticipated (e.g., no localized corrosion issues). There would be relatively little perturbation of the natural environment, so there could be more confidence in the environment after the high thermal period was completed.

EDA II was ranked next highest for the performance demonstrability criterion. Of the EDAs, it received the second-to-highest rating for uncertainties in 10,000-year postclosure performance and third highest rating for engineering acceptance factors. The lower postclosure uncertainty was related to a drift wall temperature that would never exceed 150°C, thus limiting adverse impacts to the surrounding rock (e.g., minimizing thermal expansion and contraction, development of new fractures, and related processes). The rating was lower than for EDA I, however, because greater uncertainties are associated with the effects of higher temperatures on chemical, mechanical, and other processes. In addition, EDA II contained backfill, and this

factor would result in associated uncertainties in predicting the temperature and relative humidity effects on the drip shield and waste package.

The engineering acceptance of EDA II was lowered somewhat by the backfill component because there are no precedents for using backfill to control relative humidity, and the precedents for blending are limited. The uncertainties in 100,000-year postclosure performance of EDA II is also lowered by backfill, because demonstrating the long-term performance of backfill could be difficult.

EDA IIIb was ranked third in performance demonstrability and higher than IIIa, primarily because the robust dual corrosion-resistant material, three-layer package (Alloy-22 over titanium alloy grade 7 [Ti-7] over stainless steel) is expected to have good postclosure performance. However, the uncertainties in postclosure performance are increased by the uncertainties in the behavior of the waste package materials, particularly the material interactions (e.g., Alloy-22 aging, Alloy-22 and Ti-7 stress corrosion cracking, and Ti-7 hydriding after Alloy-22 penetration) and thermal-mechanical effects on the drift wall. The engineering acceptance of the three-layer package is also uncertain. The fabrication plan involves a shrink-fit between the Alloy-22 and Ti-7 and a slip fit between the dual corrosion-resistant material and the stainless steel. This type of fabrication is complex; there are few precedents, and the process could have lower acceptance and be difficult to defend.

EDA IIIa has significant postclosure uncertainties related to the corrosion of Alloy-22 and the behavior of a repository in a high-temperature environment. There are significant uncertainties in the effects of thermal-hydrologic-mechanical-chemical coupled processes in the near field (e.g., on seepage rate and fracture flow) and it would be difficult to demonstrate that the combination of drip shields and thermal management will protect the Alloy-22 waste package barrier from localized corrosion. For the engineering acceptance factor, this EDA has a relatively high rating. The design is similar to the Viability Assessment (DOE 1998b) design.

EDA V has a relatively low ranking because of the high uncertainty in postclosure performance and engineering acceptance. The waste package surface environment would have relatively aggressive conditions (high temperatures and high relative humidity) for a relatively long period of time. As a result, uncertainties in the behavior of engineered barriers during this time are significant relative to other EDAs. Localized corrosion is anticipated on some waste packages in the aggressive environment. For the engineering acceptance measure, it would be difficult to demonstrate the postclosure function of water being driven off for the length of time anticipated or needed (i.e., heating the rock to boil water and maintaining low relative humidities). The relatively long period of hot/moist conditions would increase the time available for localized corrosion, possibly leading to earlier failure of drip shields.

EDA IV has the lowest ranking of the EDAs, primarily because of complexities related to the carbon steel waste package. Because it is important that the backfill properly control the temperature and relative humidity conditions to protect the waste package, there are uncertainties in the postclosure performance related to its use. Even if this system operates properly, the carbon steel waste packages would fail much earlier than the waste packages in the other EDAs. The welds on the very thick carbon steel package would be difficult to defend in terms of

engineering acceptance. Large amounts of welding (using robotics and hot cell) would be required, thus increasing the probability of defects.

6.2.2 Enhanced Design Alternative Ranking for the Flexibility Criterion

The flexibility criterion was divided into consideration of the potential for late changes in four factors: 1) increased capacity, if it is authorized, 2) change in preclosure period, 3) hotter spent nuclear fuel characteristics, and 4) late design changes. The increased capacity factor included a consideration of the flexibility of designs to accommodate increases in capacity up to 87,000 metric tons of heavy metal (MTHM) of commercial spent nuclear fuel and 105,000 MTHM of commercial spent nuclear fuel (as well as all DOE high-level radioactive waste and DOE spent nuclear fuel, in both cases), if additional capacity is authorized. The preclosure period included potential extensions in the closure of the repository to 100 or 300 years following start of emplacement, and the potential for closure 10 years following completion of emplacement. Late design changes, considered to occur at the end of the licensing period and before the beginning of construction, included changes in the temperature goals and blending.

Design Discriminators

The principal discriminators for the flexibility criterion were the ability to increase capacity for spent nuclear fuel, the ability to adapt to late design changes (repository temperature change, and blending change). A secondary discriminator was early closure of the potential repository; all of the EDAs would have difficulty meeting this criterion.

The ability to accommodate a long preclosure period (100 or 300 years) and the ability to accept fuel that is very young (5-year-old fuel) were both nondiscriminators. All of the EDAs are flexible enough to accommodate a longer preclosure period. For EDAs with higher temperatures (e.g., EDA III), a longer preclosure period could be beneficial to removing large quantities of heat from the waste packages and ventilation rates could be adjusted for a long preclosure period. All of the EDAs would have some difficulty accommodating 5-year-old fuel if it were to arrive near the end of the assumed 50-year baseline closure. Accepting younger fuel could force waste packages to be derated and create a possible need for larger pools to maintain blending goals. In addition, cladding goals could be violated with EDAs that include backfill in their design.

Ranking

EDAs IIIa and IIIb received the highest and equivalent rankings for all aspects of the flexibility criterion. This EDA received a relatively high rating for the increased capacity factor since there is additional room in the characterized area for expansion. EDA III could be converted from a high- to low-temperature repository fairly easily because there is space available for expanding drift spacing and the modeling efforts to define the repository performance would be simplified by going to lower temperatures. Blending could be added to this design. This EDA could not easily accommodate an early closure because of the anticipated high temperatures (e.g., cladding temperature goals could be difficult to achieve).

EDA V ranked second for this criterion. This repository design used the smallest amount of acreage of the five EDAs and could most easily accommodate increased inventories of spent

nuclear fuel and high-level waste. Similar to EDA III, a change from a hot to cold environment would be relatively simple. If blending were eliminated, however, other design elements would need to be changed (e.g., more waste packages, or a larger repository area). EDA V could not easily accommodate an early closure because of the anticipated high temperatures (e.g., cladding temperature goals could be difficult to achieve).

EDA II, which ranked third for the flexibility criterion, could accommodate an increase in the amount of spent nuclear fuel and high-level waste within the characterized area. A late design change from low- to high-temperature could be accommodated by moving the drifts closer together; however, modeling and other analyses conducted for a lower temperature environment would likely not cover higher temperature effects, and these would be difficult to "add on" unless the needed work had been carried on in parallel. A late design change to cooler temperature goals could potentially be accommodated by increasing the duration of the ventilation. If blending were eliminated, other design elements would need to be changed (e.g., more waste packages, or a larger repository area). EDA II could not easily accommodate an early closure because of the high temperatures anticipated (e.g., cladding temperature goals could be difficult to achieve, particularly with backfill).

EDA IV was similar to EDA III in the ability to accommodate an increase in waste inventory. It did not have the flexibility to accommodate a change to a low-temperature design, however, because the waste package material would not be suitable for a cool, moist environment. Blending could be added. An early closure would make cladding temperature goals difficult to achieve.

EDA I was ranked lowest for the flexibility criterion. It would have difficulty accepting an increased amount of waste. For 87,000 MTHM, the increased repository acreage needed could be accommodated in the characterized area only if less contingency area is used than in the other EDAs and the Viability Assessment design. For 105,000 MTHM, additional area would need to be characterized. A change from a cool to hot repository could not be easily accommodated because the modeling conducted for a cold repository likely would not cover high-temperature effects. If blending were eliminated, design elements would need to be changed (e.g., more waste packages or acreage would be needed). Early closure could make temperature goals difficult to achieve.

6.2.3 Enhanced Design Alternative Ranking for the Construction, Operations, and Maintenance Criterion

This criterion was divided into seven factors: 1) worker safety, 2) constructability, 3) operations, 4) maintainability, 5) handling logistics, 6) performance confirmation, and 7) off-normal access considerations (ventilation and personnel shielding needs). The scores for this criterion reflect particular advantages or disadvantages associated with these factors.

Design Discriminators

The principal discriminators between the EDAs are worker safety and operations. The discriminating aspect for worker safety was the number of repetitive actions. Secondary discriminators are constructability and handling logistics.

Aspects of construction, operations, and maintenance that made a relatively small contribution to the ranking include performance confirmation and off-normal access requirements. Four EDAs received equivalent ratings for performance confirmation, while EDA I received a higher rating, because it may be possible to eliminate the drifts dedicated for performance confirmation measurements and activities. The lower thermal effects of EDA I could permit the appropriate instrumentation to be located directly in the emplacement drifts; however, this was considered a minor benefit and had a very small influence on the overall construction, operations, and maintenance evaluation. Off-normal access requirements varied among the EDAs but were considered primarily as having cost implications, rather than being significant for the construction, operations, and maintenance criterion.

Ranking

EDA V received the highest ranking of the EDAs for the construction/operations/maintenance criterion. This EDA had the smallest repository area and least drifting and was therefore most favorable for worker safety. There were no specific concerns other than blending in the subcriteria of constructability, operations, and handling logistics.

EDA IIIa received average ratings for all but operability, for which it was slightly favored, because it did not involve the level of blending used in I, II, and V. This design was similar to the Viability Assessment design, and there are no particular advantages or disadvantages for worker safety and constructability. No complex operations are anticipated (e.g., no aging or backfill). However, there could be some difficulty with the need to stage and sequence emplacement of the relatively cool DOE waste packages so they can be interspersed among the hotter commercial spent nuclear fuel packages. This might be required in order to avoid creation of cool areas of individual drifts that might become sinks for water driven away from the hotter areas.

EDA II was given average ratings for worker safety. There are complexities related to blending that may make operations more difficult. Backfill emplacement may be difficult for the constructability factor.

For EDA IIIb, the worker safety and handling logistics ratings are average (similar to the Viability Assessment design), with no particular advantages or disadvantages. For constructability, EDA IIIb received a lower rating because of potential difficulties in constructing the three-layer waste package. The Ti-7-Alloy-22 shrink fit and slip fit with stainless steel could require special processes and more steps to inspect. For operability, this EDA was given a higher rating because complex operations are not anticipated (i.e., no aging, blending, backfill).

EDA I received relatively low ratings in both worker safety (because of more drifts and waste package emplacement operations) and in handling logistics (because of a larger number of waste packages). No special constructability or operations issues other than blending were anticipated. EDA IV received average ratings in worker safety. Because the waste package would be very heavy, low ratings were given for constructability, operations, and handling logistics. Constructability was given a low rating because the closure weld on the very thick-walled waste packages would be difficult to perform and inspect, and the support equipment would be heavier.

6.2.4 Enhanced Design Alternative Ranking for Cost Criterion

The team ranked the EDAs into two groups with respect to cost: EDAs II through V, and EDA I. The estimated costs of EDAs II through V (\$19.9 to \$21.1 billion repository life cycle costs and \$10.7 to \$11.4 billion net present value) are grouped so closely together that distinctions in rank would not be warranted. However, EDA I has a distinctly higher cost (\$25 billion repository life cycle cost and \$13.4 billion net present value) because it requires a substantially larger number of waste packages and greater length of drift construction than any of the other EDAs.

The cost drivers for the various EDAs were as follows:

- EDA I–Drip shields, additional acreage and drift length due to layout, more waste packages, additional pool capacity, welding facilities, and surface labor
- EDA II–Drip shields and backfill, waste package material costs, additional acreage, blending, and additional pool capacity
- EDA IIIa–Drip shields, waste package material costs
- EDA IIIb–Drip shields, higher waste package material costs (Alloy-22, Ti-7, stainless steel 316L)
- EDA IV–Drip shields and backfill, waste package material costs and integral filler, additional welding facility costs
- EDA V–Drip shields, waste package material costs, blending, and additional pool capacity

6.3 RESULTS OF RANKING THE ENHANCED DESIGN ALTERNATIVES

Once all of the pair-wise comparisons were completed for a particular criterion, the team determined the overall rank ordering of all of the EDAs by inspection of the pair-wise rankings. No judgment was involved at this step, since the overall rank ordering is logically implied by the results of the pair-wise rankings. For example, in ranking the EDAs within the performance demonstrability criterion, the results of the pair-wise comparisons were as follows:

- EDA I was ranked higher than each of the other EDAs.
- EDA II was ranked higher than EDAs IIIa, IIIb, IV, and V.
- EDA IIIa was ranked higher than EDAs IV and V.
- EDA IIIb was ranked higher than EDAs IIIa, IV, and V.
- EDA IV was not ranked higher than any of the other EDAs.
- EDA V was ranked higher than EDA IV.

While it is theoretically possible that such a process could fail to provide a unique rank ordering, that complication did not arise in this case. Table 6-1 indicates the ranking of the EDAs *within* each of the four criteria: performance demonstrability; flexibility; construction, operations, and maintenance; and cost/schedule.

Table 6-1. Summary Evaluations

Enhanced Design Alternative Ranking for Performance Demonstrability	Enhanced Design Alternative Ranking for Flexibility	Enhanced Design Alternative Ranking for Construction, Operations, Maintenance	Enhanced Design Alternative Ranking for Cost/Schedule
I	IIIa, IIIb	V	II, IIIa, IIIb, IV, V
II	V	IIIa	I
IIIb	II	II	
IIIa	IV	IIIb	
V	I	I	
IV		IV	

6.4 DESIGN RECOMMENDATION

The LADS core team and Management and Operating Contractor (M&O) management group used the EDA rankings to select the design to be recommended to DOE. As discussed previously, the EDAs were ranked by the LADS core team within each evaluation criterion based on the ratings and judgment using pair-wise comparisons. The basis for these rankings were reviewed and thoroughly discussed in a meeting of the LADS core team and the M&O management group. The meeting participants then considered which design, and its associated thermal goals, most consistently ranked highly against all of the four criteria. No attempt was made to explicitly weight or otherwise specify the relative value of the criteria. Instead, the team considered the consistency of rankings across the multiple criteria; an EDA that ranked well in all of the criteria was considered to be preferable to an EDA that ranked highly on one or two criteria but poorly on another.

Table 6-2 summarizes the key issues resulting from the analysis of the EDAs that were considered in arriving at a design recommendation. All of the EDAs displayed excellent postclosure performance with large margins compared to the screening criterion of 25 mrem/yr in the first 10,000 years. Key issues for discriminating among the designs related to the uncertainties in postclosure performance and the ability to demonstrate that performance. Of particular importance were those uncertainties that result from coupled thermal-hydrologic processes in the rock surrounding the drifts and thermally driven crevice corrosion of the Alloy-22 waste package material. EDAs I and II were judged to provide significantly fewer uncertainties in these areas relative to the other EDAs due to their lower temperatures, and EDA I was particularly advantageous in keeping temperatures low enough to mitigate uncertainties associated with natural system coupled processes and localized corrosion on the drip shields and waste packages.

Table 6-2. Principal Results of Analysis of Enhanced Design Alternatives

Performance Categories		EDA I	EDA II	EDAs IIIa/IIIb	EDA IV	EDA V
Performance Factors	Margin	2,500	3,550	1,500	180,000	1,250
	Time to 25 mrem	290,000 years	310,000 years	290,000/ 310,000 years	100,000 years	300,000 years
	Peak Annual Dose	85 mrem	85 mrem	215/100 mrem	1,200 mrem	200 mrem
Performance Demonstrability Factors	Rock Temperatures	Always below 96°C	Rock for several meters around drifts exceeds boiling point of water for several hundred years	Above-boiling conditions extend across most of repository	Above-boiling conditions extend across most of repository	Above-boiling conditions extend across essentially all of repository
	Waste Package Corrosion	Never enters aggressive corrosion range	Never enters aggressive corrosion range	Some waste packages in aggressive corrosion range for thousands of years	Humid air corrosion of waste packages begins as early as 100 years	Some waste packages in aggressive corrosion range for over 10,000 years
Construction, Operations, and Maintenance Factors	Number of Waste Packages	15,903	10,039	10,213	10,213	10,039
	Length of Emplacement Drifts ¹	132 km	54 km	55 km	60 km	54 km
	Key Construction, Operations, and Maintenance Issues	Operational impacts of more packages and longer drifts; blending	Blending; emplacement of backfill	Fabrication of dual corrosion-resistant material package in IIIb	Fabrication, welding, and handling thick waste packages; emplacement of backfill	Blending
Flexibility Factors	Emplacement area for 70,000 MTHM	1,400 acres	1,050 acres	740 acres	740 acres	420 acres
	Ability to Change to Lower Temperature	N/A	Requires longer ventilation	Requires changes in drift spacing	High temperature is integral to waste package performance	Requires changes in drift spacing
	Ability to Change to Higher Temperature	Requires development of larger packages and coupled models for performance assessment	Requires development of coupled models for performance assessment	N/A	N/A	N/A

Table 6-2. Principal Results of Analysis of Enhanced Design Alternatives (Continued)

Performance Categories		EDA I	EDA II	EDAs IIIa/IIIb	EDA IV	EDA V
Cost	Repository Life Cycle Cost	\$25.1 billion	\$20.6 billion	\$20.1 billion/ \$21.3 billion	\$21.7 billion	\$20.0 billion
	Net Present Value	\$13.4 billion	\$11.0 billion	\$10.7 billion/ \$11.4 billion	\$11.3 billion	\$10.8 billion

¹ Emplacement length does not include perimeter drifts, maintenance drifts, performance confirmation drifts, or contingency area. Lengths were calculated as follows:

- (a) The EDA II length (from CRWMS M&O 1999w) was divided by its number of waste packages to obtain the average drift length used for each package and associated gap.
- (b) The EDA II drift length was adjusted for the other EDAs: (I) 2.9 m were added to account for the gap increase from 10 cm to 3 m; (III and V) no change; (IV) 46 cm were added to account for the two thicker lids of EDA IV (30 cm rather than 7 cm).
- (c) The adjusted average lengths were multiplied by the number of waste packages for each EDA.

In the area of construction, operations, and maintenance, all of the EDAs except EDA I had comparable operational issues associated with the excavation of drifts and emplacement of waste packages, since these EDAs all used essentially the same number of waste packages and length of emplacement drifts. EDA I was additionally burdened in this area, which affects the likelihood of industrial accidents, because compared with the other EDAs, it required about 60 percent more waste packages and more than twice the emplacement drift length. These differences compared with the other EDAs resulted from the two additional thermal management measures that were required to achieve the low temperature goals of EDA I: use of a larger number of substantially smaller waste packages (having slightly less than 60 percent of the capacity of those used in the other EDAs), and increased spacing between the waste packages (from the 10-cm line load spacing of the other EDAs to a 3-m point load spacing).

In terms of flexibility, compared with the other EDAs, EDA I was capable of handling less additional capacity within the area that has already been characterized. EDA II was judged to be particularly flexible in its ability to change to a lower or higher temperature design, if required. A change towards the temperature goals of EDA I could be accomplished through extension of the ventilation period in EDA II, without repackaging the waste or separating the existing waste packages. In contrast, physical changes to the repository layout would be required in the EDAs having more extensive thermal effects. All of the EDAs were comparable in terms of estimated total repository life cycle cost and net present value cost except EDA I, which was about 20 to 25 percent higher than the other four EDAs, primarily because of the larger number of waste packages and additional emplacement drift length.

As noted, these assessments did not consider the possible implications of strong differential weights or values associated with any given criterion. For example, if strong weight were assigned to construction, operations, and maintenance in choosing among the designs, EDA V might have been selected despite its somewhat poor ranking against other criteria. Likewise, the team concluded that the strong performance of EDA I on the performance demonstrability criterion did not outweigh the significant worker health and safety, logistical, and cost disadvantages resulting from the substantial increase in the number of waste packages and length of underground tunneling required to achieve its temperature goals.

EDA II ranked second highest on performance demonstrability because it reduced the uncertainties in the effects of heat from the waste on the natural system compared with EDAs having more extensive thermal effects (although less than EDA I), while avoiding the complications in repository construction and operation associated with EDA I. In addition, EDA II provided reasonable operability, flexibility, and cost. EDAs III and V rank well in issues related to construction/operations/maintenance, flexibility, and cost, but not performance demonstrability. EDA IV received consistently lower rankings on all criteria except cost.

Taking all of these considerations into account, the M&O recommended that EDA II be taken forward as the candidate conceptual design for the possible Site Recommendation and License Application. Overall, it provided a good balance between the postclosure advantages of lower temperature designs (ability to reduce uncertainties about postclosure performance) and the preclosure advantages of high-temperature designs (in the areas of construction, operation, and maintenance; flexibility; and cost). The meeting participants concluded that the recommended design would be highly flexible with respect to further design optimization because of sufficient

margin with its cladding and drift wall temperature goals. Likewise, it appeared to be flexible in possible modifications toward either higher temperature or lower temperature design goals, should these goals be deemed appropriate. Because the design includes the facilities needed for blending, it is compatible with the other concepts requiring various levels of blending. Further, no additional technology development or site characterization would be needed to allow transition to cooler temperature goals by extending the preclosure ventilation duration. The performance assessment models required for cooler temperatures should be simplifications of those required for EDA II because they do not have to deal with as much thermal perturbation of the rock of the repository and should not require additional work. In the other direction, no technology development (e.g., waste packages and drip shields) would be needed to move toward higher temperature goals. The main additional work required would be to develop the performance assessment models needed to deal with the greater extent of thermal perturbation in the more-extensively heated cases.

6.5 COMPARISON OF ENHANCED DESIGN ALTERNATIVE II AND VIABILITY ASSESSMENT DESIGN

The recommended design, EDA II, is compared with the Viability Assessment design in Table 6-3.

The recommended design, EDA II, uses more area than the Viability Assessment design, but is capable of emplacing 70,000 MTHM within the upper emplacement level and more than 105,000 MTHM in the characterized area. Its wider drift spacing improves drainage and thermal independence of the drifts. Its steel ground support and invert reduce performance uncertainties attributable to the effects of concrete on radionuclide mobilization and transport in the Viability Assessment design (see Section 5.1.5.3).

The EDA II waste package design is the reverse of the Viability Assessment design. In EDA II, the corrosion-resistant material protects the underlying structural material from corrosion while the structural material supports the thinner more expensive corrosion-resistant material. In contrast, the Viability Assessment design subjects its structural material to corrosion during the thermal pulse, which delays the onset of corrosion of the underlying corrosion-resistant material beyond the thermal pulse, but which also limits the duration of structural strength. In addition, the failure mode of the Viability Assessment structural material may accelerate the failure of the corrosion-resistant material due to oxide wedging; in contrast, EDA II uses a structural material with limited expansion upon corrosion, thus limiting oxide wedging.

EDA II uses thermal management features (line loading, ventilation, and blending) to limit peak temperatures of cladding, the waste package shell, and the drift wall. Compared with the Viability Assessment, this produces more uniform temperatures along the drifts, and greater margin in meeting requirements for cladding integrity, drift stability, and avoidance of localized corrosion of the waste package materials. Figure 6-1 shows the waste package temperature and relative humidity histories for the Viability Assessment design (DOE 1998b, Vol. 3, Figure 4-5) and EDA II (CRWMS M&O 1999w). The Viability Assessment design spends about 4,000 years in the window of susceptibility for Alloy-22 crevice corrosion, while the EDA II design avoids this aggressive regime.

Table 6-3. Comparison of Enhanced Design Alternative II and Viability Assessment Design

	EDA II	Viability Assessment Design
Design Characteristics		
Areal Mass Loading	60 MTHM/acre	85 MTHM/acre
Drift Spacing	81 m	28 m
Drift Diameter	5.5 m	5.5 m
Waste Package Spacing	Line loading: 10 cm	Point loading: Spacing varies (several meters)
Total Length of Emplacement Drifts	54 km	107 km
Ground Support	Steel	Concrete lining
Invert	Steel with sand or gravel ballast	Concrete
Number of Waste Packages	10,039	10,500
Waste Package Materials	2-cm Alloy-22 over 5-cm stainless steel 316L	10-cm carbon steel over 2-cm Alloy-22
Maximum Waste Package Capacity	21 pressurized-water reactor (PWR) assemblies	21 PWR assemblies
Peak Waste Package Power to Average PWR Power (blending)	20% above average PWR package	95% above average PWR package
Drip Shield	2 cm Ti-7	None
Backfill	Yes	None
Preclosure Period	50 years	50 years
Preclosure Ventilation Rate	2 – 10 m ³ /s	0.1 m ³ /s
Performance (Central Estimate)¹ and Cost		
First / Median Drip Shield Failure	9,000 / 55,000 years	N/A
First / Median Waste Package Failure	100,000 / 325,000 years	4,000 / 165,000 years
Performance Margin	10 ³	10 ³
Time to Reach 25 mrem/yr	305,000 years	150,000 years
Peak Dose Rate	85 mrem/yr	330 mrem/yr
Time of Peak Dose Rate	630,000 years	310,000 years
Repository Life Cycle Cost (1998 \$)	\$20.5 billion	\$16.8 billion
Repository Net Present Value Cost (1998 \$)	\$10.9 billion	\$10.1 billion

¹ These performance estimates do not represent a licensing case. They are only preliminary calculations for conceptual designs.

Inclusion of a drip shield in EDA II increases the degree of defense in depth and protects the waste package from contact with chemically aggressive seepage water during the thermal pulse, when the waste package material would be most rapidly degraded by such water. The combination of backfill and drip shields also reduces uncertainty by limiting the effects of rockfall on performance. Backfill also delays the time at which the drip shield will begin to corrode, by reducing relative humidity during the thermal pulse. The thick outer carbon steel shell of the Viability Assessment design has similar objectives; however, the longevity of that shell is much less than the effective lifetime of the EDA II backfill and drip shield combination.

The result is that the first waste package failure for EDA II, other than an assumed juvenile failure, is calculated at about 100,000 years (CRWMS M&O 1999w), compared to about 4,000 years for the Viability Assessment design (DOE 1998b, Vol. 3, Figure 4-13). For EDA II, no waste packages were calculated to fail within 100,000 years. Performance margin within 10,000 years was based on a single assumed juvenile failure of one patch (310 cm²) of one waste package at 1,000 years. It was further assumed that this juvenile failure occurred under the first drip shield that failed. For the Viability Assessment, in addition to the juvenile failure, there were 17 waste package failures by localized corrosion; however, the small release area of these breaches did not produce as much dose rate at the accessible environment within 10,000 years as did the single assumed juvenile failure of one much larger patch on a single waste package.

The longer waste package lifetime and the function of most drip shields for many tens of thousands of years reduces radionuclide releases from the engineered barrier system and thus dose rate at the accessible environment. Figure 6-2 shows the dose rates at the accessible environment for the Viability Assessment design (DOE 1998b, Vol. 3, Figure 4-21) and EDA II (see Figure 5-14) over a 1-million-year period. Neither design has significant dose rates during the potential regulatory period of 10,000 years, but EDA II has considerably lower dose rate peaks at later times.

The installation of drip shields and backfill in EDA II at closure will require reliable operation of remotely controlled equipment in a high temperature environment with radiation. These tasks are not required in the Viability Assessment design, although similar capability will be required to respond to off-normal events. The remote installation tasks are mitigated in EDA II by the preclosure ventilation, which limits preclosure drift temperatures to sub-boiling, compared to about 170°C for the Viability Assessment design. Emplacement of waste packages is also different for the two designs. For the Viability Assessment design, the waste packages would be emplaced using a gantry that lifts and carries the waste packages by their ends. Due to the smaller gaps between the EDA II waste packages, the waste packages would be emplaced by equipment lifting them from below, but which would back out of the drift after emplacing the pre-assembled waste package and support hardware.

Overall, EDA II increases the estimated repository life cycle cost of the potential repository about 25 percent compared with the Viability Assessment design. This represents about an 8 percent increase in the net present value of the costs, a measure that takes into account the fact that most of the additional costs do not occur until the time the repository is closed in 2060 (after the drip shields and backfill are emplaced). Since there will be time to optimize the cost-effectiveness of the drip shield and backfill during the 50 years of repository operation, this increase in the current estimate of long-term costs is reasonable.

Figure 6-1. Enhanced Design Alternative II and Viability Assessment Temperature/Relative Humidity Corrosion Susceptibility Comparison

Figure 6-2. Dose Rate at 20 km, Central Estimate

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7. RECOMMENDATIONS AND CONCLUSIONS

This section details the recommendations and conclusions of the License Application Design Selection (LADS) core team. Section 7.1 presents the recommended design. Section 7.2 focuses on the major considerations of the recommended design (i.e., reduced uncertainties, construction and operations, technical and programmatic flexibility, and cost). Section 7.3 outlines 10 recommendations for optimizing the recommended design while preserving the basic intent of the Enhanced Design Alternative (EDA) II design. Section 7.4 presents the concluding remarks of this report.

7.1 RECOMMENDED DESIGN

The LADS study was a conceptual design process guided by general principles of decision-making. The process consisted of two phases. In Phase I, a series of basic design concepts (design alternatives) and components (design features) were evaluated for their potential value as components of a possible repository design. The EDAs were developed using this information. These EDAs were then refined and evaluated in Phase II, leading to a selection from among the alternatives. EDA II was recommended by the combined LADS team and Management and Operating Contractor (M&O) management group.

The basic elements of the recommended design are:

Design Goal: The heat generated by the waste emplaced in the potential repository should not cause boiling fronts to coalesce in the pillars between the loaded emplacement drifts. Additionally, commercial spent nuclear fuel cladding would be limited to temperatures less than 350°C. These goals permit water to shed through the pillars during the postclosure thermal period while protecting the cladding, which is known to be of significant value in containing the spent nuclear fuel.

Given these design goals, subject to enhancements during the subsequent detailed design process, the initial configuration of the recommended design is as follows:

- Areal mass loading: 60 metric tons of heavy metal/acre
- Emplacement drift spacing: 81 m (center to center)
- Entire emplacement in the upper emplacement level of the characterized repository (about 1,050 acres)
- Total emplacement drift length: 54 km
- Total access drift length: 33 km
- Emplacement drift diameter: 5.5 m
- Ground support: Steel
- Invert: Steel frame with sand or gravel ballast

- Drift loading: Line loading with 10 cm between waste packages
- Drip shields: Continuous 2-cm titanium alloy grade 7 (Ti-7); self-supporting
- Backfill: Granular material
- Waste package: 2-cm thick Alloy-22 over 5-cm thick stainless steel 316L, with a capacity of 21 pressurized-water reactor (PWR) spent nuclear fuel assemblies
- Heat output: Average PWR waste package output of 9.8 kW, with blending to keep the hottest packages within 20 percent of the average
- Repository ventilation: Approximately 2 to 10 m³/s continuous preclosure airflow in emplacement drifts for temperature control

Predictions of the central performance values for the time periods of interest show that the recommended design is a conservative design relative to currently assumed regulatory standards. As noted in Section 7.3, it will be necessary to optimize the recommended design before this design can be brought forward to the level of detail required for the possible Site Recommendation and License Application. The design goals will remain fixed while other elements of the design are refined to balance safety, cost, flexibility, and constructability.

7.2 MAJOR CONSIDERATIONS OF THE RECOMMENDED DESIGN

The Viability Assessment concluded that Yucca Mountain remains a promising site for a geologic repository; however, uncertainties remain about key natural processes, the preliminary design, and how the site and design would interact (DOE 1998b, Overview, p. 30). With these observations in mind, the LADS team set out to provide a design concept that would provide a path forward while allowing key uncertainties about natural processes to be mitigated, reducing possible detrimental interactions with the naturally occurring site materials, and providing a focus for the design, performance assessment, and site assessment activities. The recommended design provides a good balance of the ability of lower temperature designs to reduce uncertainties about postclosure performance and the preclosure advantages that designs with greater thermal effects can offer in the areas of construction and operations, flexibility, and cost. The major evaluation criteria of performance demonstrability; construction, operations, and maintenance; flexibility; and cost/schedule were evaluated for the EDAs. Within each of these categories, the following areas particularly favor the recommended design.

Screening Criterion

Preliminary performance assessment projections indicate that the recommended design, if implemented at Yucca Mountain, would perform extremely well with respect to a screening criterion of 25 mrem/yr to a critical population at 20 km from the repository during the first 10,000 years. A calculated dose rate of 25 mrem/yr would not be reached for more than 300,000 years.

Performance Demonstrability

The recommended design offers a number of advantages for the licensing safety case compared with designs with more extensive thermal effects (including the Viability Assessment design). The recommended design reduces or avoids uncertainties associated with the thermal pulse when larger quantities of water could possibly pool above the repository horizon. This could occur if the temperatures are high enough to dry out almost all of the rock in the potential drainage paths in the drift pillars (as occurs in the designs with greater thermal effects). If such pooling occurs, significant quantities of water could flow through fast paths in the dried-out area, and some could enter the repository emplacement drifts and contact very hot drip shields or waste packages, thus promoting corrosion. The recommended design avoids the pooling effect by keeping large areas of very wide pillars cool enough to allow the water above the drifts to move around the drifts and drain through the pillars, although some of the flow paths could intersect the drifts. The recommended design would mobilize water in the pores of the rock immediately around the emplacement drift. However, this effect would extend for only several meters, and the time at which rock would be elevated above the boiling point of water would be only several hundred years.

The recommended design has three further advantages in making the licensing argument. First, while the design would heat the rock above the boiling point of water for several meters around the emplacement drift, this would occur for a significantly shorter time than expected with a design having more extensive thermal effects. By raising only a small quantity of the rock mass above the boiling point of water and doing so for a relatively brief time period, the potential for long-term hydrological and geochemical alteration of the host rock is reduced. This commensurately reduces the uncertainties associated with modeling the performance of the host rock. Second, the wide drift spacing reduces the thermal and hydrological coupling of the drifts, allowing them to function independently. This simplifies the analysis of repository performance and allows the segregation of cooler waste streams (e.g., U.S. Department of Energy [DOE] high-level radioactive waste) in separate drifts from the hotter commercial spent nuclear fuel without affecting throughput. Finally, the design does not expose any waste packages to temperature/humidity conditions within the aggressive crevice corrosion window of susceptibility for Alloy-22; further, the waste packages fall below the temperature threshold within a few hundred years. As a result, the Alloy-22 waste package material is subject only to very slow general aqueous corrosion from seepage water and/or condensation. The potential for separate emplacement of hotter and cooler waste packages avoids the need for a careful staging and sequencing of the emplacement of some of the cooler DOE waste streams (e.g., high-level radioactive waste) in the same drifts as the hotter commercial waste packages, as was assumed in the Viability Assessment design and the EDAs with more extensive thermal effects.

Construction, Operations, and Maintenance

The recommended design achieves the operational benefits of the designs with more extensive thermal effects, as it permits the use of larger waste packages and shorter emplacement drifts. (In contrast, EDA I, the very low-temperature alternative, required 60 percent more waste packages, and more than twice the emplacement drift length, leading to an increase in the potential for industrial accidents during construction and operation.) The recommended design

does require additional access drift excavation, compared with designs with greater thermal effects.

An additional operational flexibility that is inherent in the recommended design is the potential to separate cooler spent nuclear fuel and defense high-level radioactive waste from the hotter spent nuclear fuel. For example, defense high-level radioactive waste and commercial spent nuclear fuel could be placed into separate drifts, if appropriate. This would be allowed because the combination of blending and wide drift spacing reduces the possibility of a warmer drift causing water to move into the cooler drifts. In effect, a drift filled with the cooler waste packages would see conditions similar to the long-term ambient conditions.

Flexibility

The recommended design provides a high degree of technical and programmatic flexibility, while allowing major progress toward a design that can meet the licensing criteria. There are major elements of the repository program that require the availability of long-term data. To satisfy these requirements, a number of studies are currently underway. Long-term corrosion testing is in progress and will continue for decades. The drift-scale heater test is in progress and will yield significant data in several years. The transport studies at Busted Butte will also yield important information. Drilling in Nye County, Nevada, is helping to fill gaps in the data concerning the far-field. On the other hand, non-program commercial spent nuclear fuel storage programs are proceeding, and a regulatory standard has not yet been proposed by the U.S. Environmental Protection Agency. With such a large number of unknowns, the design must allow the program to proceed and yet maintain some flexibility for future decision makers.

The recommended design provides a path forward that does not preclude future revision of major program goals or design attributes. These revisions may come about due to revelations caused by new or revised data; changes in the circumstances of key drivers, such as timing of waste receipt at the repository; response by licensing agencies to the initial licensing submittal; or shifts in national priorities that may dictate increases in repository capacity or time of repository closure.

The recommended design is highly flexible with respect to further design optimization because of sufficient margin with its cladding and drift wall temperature goals. Likewise, it is flexible and allows modifications toward either higher temperature or lower temperature design goals, should these goals be deemed appropriate. Because the design includes the facilities needed for blending, it is compatible with the other EDAs requiring blending, as well as those that do not. Further, no additional technology development or site characterization would be needed to allow a move toward cooler temperature goals by extending the preclosure ventilation duration. The performance assessment models required for cooler temperatures would be simplifications of those required for EDA II because they would not need to deal with as much thermal perturbation of the rock of the repository and should not require additional work. In the other direction, no technology development (e.g., waste packages and drip shields) would be needed to move toward higher temperature goals. No additional site characterization would be needed to allow transition to lower temperature goals by extending the preclosure ventilation period. The main additional work required would be to develop the performance assessment models needed to deal with the greater extent of thermal perturbation in the more-extensively heated cases. The

recommended design retains the necessary flexibility for future decision makers. This flexibility will allow the scientific and engineering data gathered in the future to influence the repository design, as warranted. The long preclosure ventilation period allows time to gather additional data that might support modifications to the potential repository before closure. For example, provision of defense in depth through a drip shield added only at closure allows for optimization of the design that is based on further data and analysis during the operational period of the potential repository. Finally, although the design requires 40 percent more area than the Viability Assessment design, it leaves room to accommodate 105,000 metric tons of waste, if such an increase in capacity is authorized, within an area that has already been characterized.

Cost/Schedule

The estimated cost of the recommended design is similar to the cost of the designs with greater thermal effects and is 25 percent lower than the very low-temperature design of EDA I. Although the estimated cost is about 20 percent higher than the Viability Assessment design, most of these costs are associated with fabrication and emplacement of the drip shield and installation of backfill, and would not be incurred until closure of the repository. The net present value cost of the recommended design, which takes into account the long delay in the expenditures on the drip shields, is only about 8 percent higher than the net present value cost of the Viability Assessment design. These costs were not included in the Viability Assessment design because the consideration of a defense-in-depth strategy had not matured to the point that a drip shield or other defense-in-depth barrier was considered in the base design case.

7.3 RECOMMENDATIONS FOR OPTIMIZATION OF THE RECOMMENDED DESIGN

The M&O recommendation is a conceptual design. The various design elements considered during the study were conceptual in nature; for example, the study focused on the general design of the waste package (the type and arrangement of materials) rather than on the precise dimensions and fabrication techniques. More detailed design and site characterization activities will need to occur following the LADS project and prior to the possible Site Recommendation and License Application. By keeping the evaluations at a conceptual-design level, the LADS team was able to consider a wide range of design options despite the differences in data available for various design elements. However, considering the work to be performed in the ensuing time prior to the possible Site Recommendation and License Application, the M&O arrived at several recommendations to optimize the recommended design while preserving the basic intent of the selected concept. It is intended that these specific recommendations, coupled with the detailed planning for related future activities, form the basis for replanning the work to be performed in this time frame.

Recommendation 1—Design Basis Heat Output

Investigation of the EDAs revealed the importance of thermal management as a major factor (postclosure considerations) in the design of the potential repository. The M&O recommends that a design basis be established for the heat output characteristics of the waste packages to be emplaced in the repository.

Recommendation 2–Modular Design and Construction

The M&O recommends that the study of modular design and construction (CRWMS M&O 1999hh) be revised to reflect the recommended design, including consideration of the need for blending and potential modularization of the construction of the subsurface.

Recommendation 3–Thermal Management

The M&O recommends that a comparison of the costs and benefits of ventilation and other thermal management techniques be performed during the refinement of the recommended design. Design refinement should include consideration of the logistical issues of waste package spacing necessary to achieve a line load, and the thermal effects of preclosure rockfall in the emplacement drift. A review should also assess the thermal effects of segregating waste types in separate drifts.

Recommendation 4–Extended Ventilation

The M&O recommends that the drift layout presume ventilation for the 50-year preclosure period as the reference design case. However, the design should not preclude the possibility of operating the ventilation system for a longer period of time if that should be necessary in the future. This would allow maximum flexibility to meet the thermal goals, should future changes to the postclosure thermal goals be necessary.

Recommendation 5–Waste Package Size

The M&O recommends that optimization studies be performed on waste package sizes to determine if it is reasonable to provide an increased level of standardization for the commercial spent nuclear fuel. The preliminary blending studies showed that fewer than 200 of the commercial spent nuclear fuel waste packages require the smaller 12 PWR assembly capacity waste package. Derating should be considered for the 21 PWR/44 boiling-water reactor assembly capacity waste package as a trade-off against developing two waste package sizes for commercial spent nuclear fuel.

Recommendation 6–Single Corrosion-Resistant Material Waste Package

The M&O recommends consideration of the waste package design with Alloy-22 over stainless steel. Focused confirmatory testing on Alloy-22 should be continued. If it is determined that stainless steel can be an effective barrier to long-term radionuclide release, detailed models that include stainless steel as a barrier to waste package degradation should be developed and implemented.

Recommendation 7–Corrosion-Resistant Material Canisters

Based on the Phase I analysis of canistered fuel (CRWMS M&O 1999o), the M&O recommends consideration of an additional barrier for the small quantities of commercial spent nuclear fuel without intact zirconium-based cladding, as a cost-effective way to improve performance of the repository. Review of dose contributions predicted by performance assessment of the Viability Assessment design has indicated that juvenile failure of high-level radioactive waste packages

are comparable to commercial spent nuclear fuel waste packages as contributors to dose at the accessible environment. Consideration should also be given to extending these efforts to those portions of the DOE spent nuclear fuel and high-level radioactive waste that do not include a highly corrosion-resistant barrier as part of the waste makeup (such as the vitrified glass logs).

Recommendation 8–Invert Design

The M&O recommends that a steel invert with granular ballast and steel ground support be used. Testing to determine the diffusion coefficient and thermal conductivity of an invert should be undertaken. Compatibility among the invert, waste package support, and waste packages should also be studied.

Recommendation 9–Drip Shields

The M&O recommends development of a drip shield design that can be defended in the licensing process and modeled adequately for total system performance assessment. The LADS team assumed a Ti-7 drip shield during its deliberations. As Ti-7 is one of the corrosion-resistant materials that can perform in the range needed for the program, work should be undertaken to develop adequate corrosion and structural models and data for this material. Materials and the configuration for the drip shield should be designed, and the timing of the drip shield placement should be determined. Studies of other configurations and materials, as well as potential developmental programs, should be undertaken. Due to the timing of the drip shield emplacement, priority should be given to a defensible design for potential licensing. The work to fully optimize the drip shield (or other defense-in-depth feature) and potentially reduce its cost can be undertaken after this milestone.

Recommendation 10–Backfill

The M&O recommends that a study be undertaken to determine the value of backfill relative to construction/operation/maintenance, performance demonstrability, and cost.⁷

7.4 CONCLUSIONS

This report documents a design recommended by the LADS core team and M&O management as an appropriate initial design to start the Site Recommendation and License Application design process. The recommended design satisfies all of the total system performance objectives and the margin by which it satisfies these requirements has been quantified. Potential options and recommended design optimizations that could provide additional flexibility in moving towards a possible Site Recommendation and License Application have been developed and quantified. The costs and the benefits of key design features have been identified, documented, and evaluated.

This design recommendation was based on a systematic and documented process of identifying relevant evaluation criteria, including a quantitative cost evaluation and factors related to performance demonstrability, flexibility, and construction/operations/maintenance. Issues related to

⁷ This task was accomplished as documented in *Evaluation of EDA II Without Backfill* (Snell 1999b).

performance standards, defense in depth, repository safety strategy, and appropriate program enhancements were considered during the evaluations.

Sufficient flexibility has been maintained in the recommended design to allow for changes such as those engendered by environmental concerns, new scientific and engineering knowledge, or a shift in national priorities that may dictate a change in repository capacity or time of repository closure. The recommended design provides a path forward that does not preclude future revision of major program goals or repository design attributes. The detailed documentation provided in this report is provided in the context of the available information, current standards, and DOE guidance.

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10 CFR 72. Energy: Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High-Level Radioactive Waste. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 238589.

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8.3 PROCEDURES

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APPENDIX A

LICENSE APPLICATION DESIGN SELECTION
PROJECT DIRECTION AND GUIDANCE

APPENDIX A

LICENSE APPLICATION DESIGN SELECTION PROJECT DIRECTION AND GUIDANCE

U.S. Department of Energy Level 2 Milestone

The U.S. Department of Energy (DOE) designated a Level 2 Milestone that is to be a DOE letter report (Dyer 1998) that documents the selection of the initial Site Recommendation and License Application design concept and attendant options to start the Site Recommendation/License Application design process. The selection will be based on quantitative cost/benefit analyses of performance allocations associated with appropriate standards, the defense-in-depth approach, the repository safety strategy, and appropriate program enhancements. The design concept selected will satisfy the appropriate requirements (total system performance objectives and associated margins) and will allow the design to move forward to the Site Recommendation and License Application phases. The selection will include the appropriate potential options. These options will be those that support both the Site Recommendation and the License Application, while also being flexible enough to support the environmental impact statement record of decision (see the Yucca Mountain Site Characterization Office Milestone Description and Supporting Information Multi-Year Planning System database, Version 2.0, PSS ID M2MQ).

Management and Operating Contractor Level 3 Milestone

The Level 3 Milestone for the License Application Design Selection report was based on the above requirements for the Level 2 Milestone, as well as the following DOE guidance:

Design Alternatives: The [Management and Operating Contractor] shall plan for a rigorous (quantitative) evaluation of design alternatives and design options based upon those identified in the [Viability Assessment (DOE 1998b)] product and License Application plan for inclusion in the License Application. The planning for these evaluations shall clearly distinguish significant License Application issue resolution points that must be satisfied in order to complete the evaluations. The evaluations will support a strategy to quantitatively evaluate major design alternatives and design options prior to the final License Application reference design selection and follow-on License Application design activities (Dyer 1998).

The milestone description and evaluation criteria for the License Application Design Selection report that satisfy the Level 3 Milestone are as follows:

This milestone is a report to DOE documenting a recommended selection of the appropriate initial Site Recommendation and License Application design and appropriate options to start the Site Recommendation/License Application design process. The recommendation will be based upon a quantitative cost/benefit analysis involving performance allocation associated with appropriate standards, defense-in-depth approach, repository safety strategy, and appropriate program enhancements at that point in time. The design recommendation will satisfy appropriate requirements (total system performance objective and associated margin) and allow design to move forward to Site Recommendation and License

Application. The recommendation includes the appropriate potential options that could be carried to Site Recommendation/License Application to allow appropriate flexibility to support the [environmental impact statement record of decision]. Conclusions and recommendations need to be judged reasonable, supportable, traceable, and [be] clearly stated when evaluated in the context of the available information, standards, and DOE guidance (see the Yucca Mountain Site Characterization Office Milestone Description and Supporting Information Multi-Year Planning System database, Version 2.0, PSS ID RPA451M3).

APPENDIX B

**LICENSE APPLICATION DESIGN INTEGRATION
GROUP GUIDANCE AND DIRECTION**

APPENDIX B

LICENSE APPLICATION DESIGN INTEGRATION GROUP GUIDANCE AND DIRECTION

Table B-1 documents and summarizes the guidance and direction given by the License Application Design Integration Group to the License Application Design Selection (LADS) team during the LADS process. For each topic where guidance or direction was given, the License Application Design Integration Group direction is stated, accompanied by the License Application Design Integration Group meeting reference and the LADS team implementation of that guidance or direction (Brocoum 1999).

Table B-1. Policy Guidance Issues Discussed by the License Application Design Integration Group

Topic of Discussion	License Application Design Integration Group Meetings Where Issues Were Discussed	Policy Direction	License Application Design Selection Project Implementation
Earliest Time of Repository Closure	1/19/99: Discussion 7 1/19/99: Attachment 7 2/01/99: Action item 3 2/11/99: Action item 2 2/11/99: Action item 3 2/11/99: Attachment 2	Although the <i>Civilian Radioactive Waste Management System Requirements Document</i> (DOE 1999) currently requires the capability to close the repository within 10 years after the end of emplacement, the Site Recommendation/License Application reference design should be capable of closure within 50 years of the start of emplacement. A change to the requirements document (DOE 1999) will be proposed.	Initial analyses assuming closure 10 years after the end of emplacement were revised. All enhanced design alternative (EDA) analyses were based on a minimum closure period of 50 years.
Consideration of Long-Term Peak Dose Rate	1/19/99: Action item 5 1/19/99: Discussion 4 1/22/99: Discussion 6 1/22/99: Attachment 4 2/11/99: Action item 7	Although the proposed 10 CFR 63 (64 FR 8640) compliance period is 10,000 years, and the U.S. Environmental Protection Agency requirements have not been issued yet, some consideration should be given in the evaluation criteria for long-term peak dose rate.	The time to 25 mrem and peak annual dose were included in the performance factors addressed in the Phase II evaluation criteria.
Requirements for Enhanced Access	1/19/99: Action item 3 1/22/99: Action item 2 1/22/99: Discussion 4 1/22/99: Attachment 2 2/01/99: Attachment 5 2/01/99: Action item 4 2/11/99: Attachment 3 3/11/99: Discussion 1	Enhanced access should be a requirement for all EDA design concepts. Enhanced access to the emplacement drifts should be assumed for off-normal and upset conditions only. The allowable dose rate without portable shielding should be increased from 100 mrem (possibly to 200 mrem), and a two-step dose rate allowance should be considered, both with and without portable shielding.	Enhanced access designs were eliminated as stand-alone design concepts, and enhanced access was required of all EDA design concepts. A two-step shielding approach was considered, with combined dose rate, including portable shielding, limited to 25 mrem/hr.

Table B-1. Policy Guidance Issues Discussed by the License Application Design Integration Group (Continued)

Topic of Discussion	License Application Design Integration Group Meetings Where Issues Were Discussed	Policy Direction	License Application Design Selection Project Implementation
Defense-in-Depth Analysis	1/19/99: Discussion 8 2/01/99: Discussion 7 2/01/99: Action item 1 2/11/99: Attachment 1 3/11/99: Discussion 22 3/22/99: Discussion	The defense-in-depth analyses should address the long term (100,000 and 1 million years), in addition to the 10,000-year compliance period to highlight the contributions of the natural barrier systems, as well as the engineered systems.	Defense-in-depth analysis is currently ongoing to address these issues.
Aging and Surface Storage versus Subsurface Storage with Ventilation	2/18/99: Discussion 2/18/99: Attachment 3 2/18/99: Attachment 4 3/11/99: Discussion 2 3/11/99: Discussion 3	Consideration of extended surface storage (aging) for 25 to 50 years was not preferable. Surface storage for aging and blending should be minimized, and subsurface storage with additional ventilation should be considered as an alternative.	The original analyses, which considered 25 to 50 years of surface aging, were revised to replace surface aging with aggressive preclosure ventilation.
Screening and Evaluation Criteria	1/22/99: Attachment 4 2/11/99: Discussion 3/11/99: Discussion 18 3/22/99: Attachment 1	Environmental considerations should be changed, from screening criteria to evaluation criteria, since all EDAs have acceptable environmental impacts.	The Phase II evaluation criteria were revised to change environmental considerations from a screening criterion to an evaluation criterion within performance demonstrability.
Constraints, Goals, and Considerations	1/19/99: Action item 6 1/22/99: Action item 1 1/22/99: Discussion 3 1/22/99: Attachment 1 2/01/99: Closed action items	Guidance was given with regard to the development and evaluation of EDAs. A constraint is to be considered a requirement; a goal is something design should strive to meet; and a consideration is not required, but should be considered for the design.	The final EDAs reflect the evolution from the initial EDAs, in accordance with this guidance.
Qualification of Data and Software Required for LADS	5/03/99: Discussion 1 5/06/99: Discussion 2 5/13/99: Action item 2 5/13/99: Discussion	Since the LADS effort was to produce a conceptual design report, a graded quality assurance approach is acceptable.	A graded quality assurance program will be applied using the appropriate procedures.
Repository Design Capacity and Licensing Analysis	2/01/99: Discussion 15 5/20/99: Action item 2 5/20/99: Attachment 5	Although the current <i>Civilian Radioactive Waste Management System Requirements Document</i> (DOE 1999) requires the design to consider 87,000 metric tons of uranium of commercial spent nuclear fuel, all performance assessment and licensing activities will be limited to 70,000 metric tons of uranium of waste. However, the design should not preclude potential expansion to 105,000 metric tons of uranium of commercial spent nuclear fuel.	All performance assessment evaluations were performed on the basis of 70,000 metric tons of uranium of waste (63,000 metric tons of uranium of commercial spent nuclear fuel). Design flexibility was one of the Phase II evaluation criteria.

Table B-1. Policy Guidance Issues Discussed by the License Application Design Integration Group (Continued)

Topic of Discussion	License Application Design Integration Group Meetings Where Issues Were Discussed	Policy Direction	License Application Design Selection Project Implementation
LADS Decision Process	12/16/98 meeting with U.S. Department of Energy (DOE) and Management and Operating Contractor (M&O) Management ¹	After due consideration of a range of alternative decision processes, it was agreed that a less-structured decision process would be followed to provide for DOE flexibility in considering all available information in arriving at a design selection.	Project planning was developed to implement a decision process consistent with the DOE guidance. Approach includes explicit evaluation criteria, rating of alternatives against criteria, but not value modeling.
LADS Decision Process: Ranking of EDAs	12/16/98 meeting with DOE and M&O Management ¹	A decision was made to rank the EDAs against each of the evaluation criteria and provide to the DOE. The DOE will select the Site Recommendation reference design.	The LADS decision process was developed to implement the ranking process, including use of EDA evaluations and pair-wise comparisons to arrive at a ranking.

¹The 12/16/98 meeting with M&O and DOE management was prior to the first License Application Design Integration Group meeting.

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APPENDIX C
OTHER CONSIDERATIONS

APPENDIX C

OTHER CONSIDERATIONS

This appendix addresses other engineering and design studies, previously or currently performed, that identify alternative designs, as well as the relationship between U.S. Nuclear Regulatory Commission (NRC) issues (key technical issues [KTIs] and disruptive events) and the enhanced design alternatives (EDAs). The engineering and design studies cited include those from the operations areas in the Yucca Mountain Site Characterization Project Management and Operating Contractor contract, systems engineering and integration, waste package operations, subsurface/engineered barrier system operations, and surface facilities operations. Additionally, waste management and integration studies are addressed.

The NRC KTIs are addressed as they apply to the EDA evaluation.

Early Evaluations of Disposal Alternatives (Before 1990)

As early as 1979, options for the disposal of spent nuclear fuel for light-water reactors were explored. The National Waste Terminal Storage Program addressed several processing alternatives. One alternative involved end-fitting removal, chopping, and voloxidizing of the fuel. Also considered was combining the fuel chopping and voloxidizing with vitrification and encapsulation, along with uranium and plutonium extraction (DOE 1979). End-fitting removal, fission gas venting and resealing, fuel consolidation and fuel shearing, and immobilization in a solid matrix (versus unmodified assemblies) were also evaluated. Waste package materials evaluated included titanium and titanium alloys, nickel-based alloys, cast iron, and cast steels. Backfill material alternatives evaluated included sodium or calcium bentonite, quartz sand, basalt, tuff, serpentine, desiccants, and calcium sulfate (DOE 1981).

In 1983, material evaluations for canisters, overpacks, and horizontal borehole liners were performed. Materials suggested were 304L, 321, 316L stainless steels, 1020 carbon steel, and Incoloy 825 (Russell et al. 1983, p. 1).

Saturated zone repository locations were evaluated in comparison to unsaturated zone locations (Johnstone et al. 1984, p. i). Self-shielded waste packages in-drift, both vertically or horizontally emplaced in the drift floor or wall, were evaluated. Sealing concepts for penetrations in the underground facility were also evaluated (Fernandez and Freshley 1984, p. 7). These evaluations were completed in 1984.

Various materials for waste packages and packing material were evaluated, including titanium and titanium-steel composites, glass waste-canisters inside a metal package, and tuff packing outside the canister (O'Neal et al. 1984, p. 6). Three copper-based materials were evaluated and found feasible for waste packages (Acton and McCright 1986, p. 1).

Overall repository storage concepts were also developed. Vertical boreholes containing one waste package each, horizontal boreholes containing multiple waste packages, and various ramp and access shaft designs were evaluated (Jackson 1984, p. v). Self-shielded waste packages emplaced in the drifts, vertically in the floors and horizontally in the walls, were evaluated. It was recommended that self-shielded waste packages be dropped from consideration and

horizontal emplacement be developed to a degree equal to vertical emplacement (Gram et al. 1985, p. i-ii). Cost comparisons indicated that horizontal emplacement was less costly than vertical emplacement (Stinebaugh and Robb 1987, p. 5-1).

A two-stage repository waste handling design was evaluated. In this design, one building was used for intact spent nuclear fuel at 400 metric tons of heavy metal (MTHM)/year and another building was used for consolidated spent nuclear fuel at 3,000 MTHM/year (MacDougall 1985). Six different surface locations east of Yucca Mountain were evaluated as surface facilities locations; one was selected for conceptual design (Neal 1985, p. i).

The Site Characterization Plan (DOE 1988) required by the Nuclear Waste Policy Act was based on a conceptual design that was developed to function in concert with the natural features and characteristics of the Yucca Mountain site. Details of the conceptual design are reported in MacDougall et al. (1987). The design was based on 57 kW/acre⁸ thermal loading and it was expected that 1,380 acres would be used for emplacement. The repository emplacement drifts generally dipped with the rock strata; the underground facility would have been developed contiguously on both sides of the Ghost Dance fault. Small, thin-walled stainless steel waste packages were to be emplaced in vertical or horizontal boreholes. An important alternatives study addressed assessment of the feasibility of disposing waste in horizontal configurations. The conceptual design examined alternative locations for the waste emplacement ramp, the number of accesses, and alternative layout schemes. The conceptual design examined alternative drift shapes and sizes and addressed emplacement hole orientation, ventilation, ground support, and excavation, handling, emplacement, and retrieval equipment requirements. This conceptual design also addressed questions related to variability in the initial thermal characteristics of the waste stream, and examined area requirements for thermal loads ranging from 40 to 80 kW/acre.⁹

Recent Evaluations of Other Alternatives (Since 1990)

Alternative waste package designs continued to be evaluated after 1990. Disposal containers and monitored retrievable storage (MRS) facility canisters were evaluated, including small, stainless steel, thin-walled disposal containers with square MRS canisters, titanium, high-nickel alloy, alumina/stainless steel, bimetallic containers, and containers with coatings and fillers (Nelson et al. 1989). Of the 41 different materials reviewed for a thin-walled container, titanium alloy grade 12, Alloy C-4, Alloy 625, and Alloy 825 were recommended for further evaluation (Van Konynenburg et al. 1993). Different waste package designs, capacities, and emplacement modes were evaluated for cost, lifetime, and radionuclide release for 10,000 to 100,000 years. Multi-barrier disposal containers, large and small waste packages, and vertical borehole and in-drift emplacement of these at varying thermal loads were evaluated (CRWMS M&O 1993b, p. ii).

Vertical emplacement in the repository received further evaluation and recommendation in 1989 (Stinebaugh et al. 1989), while horizontal emplacement of single and multiple waste packages in the drift wall and boreholes was evaluated for feasibility, cost, and possible limitations (CRWMS M&O 1993c). See the alternative concepts report for a comprehensive description of

⁸ This is equivalent to about 49 MTHM/acre for 10-year-old fuel.

⁹ This is equivalent to about 34 to 69 MTHM/acre for 10-year-old fuel.

emplacement, retrieval, and backfilling for the advanced conceptual design (CRWMS M&O 1993d).

A description of a potential geologic repository that could be located at Yucca Mountain, Nevada has been documented (DOE 1996b). It presented some historical information, but primarily addressed a conceptual repository design and a concept of how the repository would operate. Included was a general look at aboveground and belowground repository operations, and a review of the expected long-term performance of the repository. The conceptual design consisted of receiving the waste at the surface of the repository, placing it in robust, metal waste packages, placing the waste packages horizontally in open emplacement drifts, monitoring the emplaced waste for a period of time and, finally, sealing and closing the repository. The concept was considered a high thermal load repository which covered about 970 acres located on both sides of the Ghost Dance fault, spaced the emplacement drift spacing a little more than 22 m apart, and had a calculated maximum drift wall temperatures between 150 and 160°C.

Alternatives associated with the treatment of spent nuclear fuel before it reaches the potential repository at Yucca Mountain have been evaluated. Multiple element sealed canisters, sealed at the reactor sites, shipped to the MRS facility, and then eventually shipped to the repository, were evaluated (CRWMS M&O 1992a, p. iii). Treatment at the MRS facility, including pass-through directly to rail cask, rail cask transfer to train, dual-purpose casks (transport and storage), and universal casks (transport, storage, and disposal) were evaluated. Additionally, shipping directly to the repository from western United States reactors was considered (CRWMS M&O 1992b, p. 12). Multi-use and multi-function canisters of various sizes for storage, transportation, and disposal were evaluated as well. These included uncanistered fuel, universal casks, transportable storage casks, and universal canisters for single and multiple assemblies. Considered in these evaluations were multi-purpose canisters (MPCs) loaded at reactor sites, as well as the MRS facility, all large MPCs from reactor sites, small MPCs for low thermal loading, and both large and small MPCs and universal casks (CRWMS M&O 1992c; CRWMS M&O 1993a). Dual purpose transportable storage casks, multi-purpose units, and MPCs were again evaluated, and the MPC was selected for design (DOE 1994, p. ES-1).

Many types of waste package transportation equipment were evaluated for use in the repository. These included rubber-tired and crawler-drive, diesel-powered and electric-powered rails and monorails (CRWMS M&O 1993e; CRWMS M&O 1997d). Alternatives for three different waste package transport concepts for in-drift emplacement (with and without two main drifts) were evaluated (CRWMS M&O 1994a). Retrieval capability and period of potential retrievability were evaluated for periods of 50, 100, and 200 years (CRWMS M&O 1994d, p. vii).

Thermal loading was evaluated with respect to performance, cost, safety, and operability (CRWMS M&O 1994b, p. iv). The effects of ventilation, waste package spacing within a drift, drift spacing, edge loading, and pre-aging spent nuclear fuel on thermal loading were evaluated (CRWMS M&O 1994c). Drift wall, cladding, and zeolite temperature limits were evaluated for an alternate low thermal loading (CRWMS M&O 1996b, p. vii).

Galvanic (cathodic) protection of the waste packages and chemical conditioning of the backfill were evaluated (CRWMS M&O 1993f; CRWMS M&O 1997a), as were several options for the disposal of site-generated waste.

Various sizes of waste packages (large, medium, and small) and small shielded and unshielded waste packages were evaluated, including advanced conceptual design waste packages and emplacement options for MPC in-drift and alcove emplacements. Since evaluations were limited to in-drift emplacement, borehole emplacement, universal waste containers, and Site Characterization Plan/Conceptual Design Report waste packages were dropped (CRWMS M&O 1997c; CRWMS M&O 1994a).

Design options for the waste package have been documented (CRWMS M&O 1996a, Vol. III). Waste packages containing multiple tube-type canisters acting as thermal shunts to aid in transferring heat to the waste package shell were also addressed. Interlocking aluminum plates used as spent nuclear fuel canisters were proposed to separate the tubes into clustered assemblies.

Following the submittal of the Viability Assessment (DOE 1998b) to Congress in 1998, the U.S. Geological Survey also submitted a report (Anderson et al. 1998). This report contained several alternative recommendations. For example, steel sets and steel lagging, rather than pre-cast concrete, were recommended for drift ground support. Limiting repository temperatures to a maximum of 100°C, using natural circulation for postclosure ventilation, and continued and continuous monitoring of performance were also recommended.

Alternative program implementation for constrained funding has been addressed (CRWMS M&O 1998d). Alternatives evaluated include options in transporting spent nuclear fuel to the repository, developing the repository in modules, and the timing and rates of operation of the components of the system. To anticipate and respond to possible funding constraints, the U.S. Department of Energy (DOE) has analyzed alternative program implementation approaches to reduce the high appropriation requirements expected during construction of the repository while retaining the 2010 target date for the start of disposal. The analysis considers ways to allow the repository's capabilities for waste acceptance and disposal to be built in segments, or modules, at a lower initial cash flow, so operation can begin at useful levels before full capabilities have been constructed. (The modules examined here are based on relatively small modifications of the Viability Assessment designs for transportation, surface, and underground facilities, rather than new designs developed specifically for the purpose, such as those considered in the modular design/phased construction design alternative described in Section 4.3.8.)

Supportive of many alternative designs, including modular design, is the consideration of lag storage. Utilization of lag storage would require revisions to the Civilian Radioactive Waste Management System requirements document (DOE 1999) and is a consideration in this study. The primary purpose of considering lag storage is to propose ways in which the Monitored Geologic Repository (MGR) could enhance thermal management while continuing to accept spent nuclear fuel and high-level radioactive waste when there are problems at the MGR (e.g., inability to process and emplace waste or inability to unload shipping casks), and to continue emplacing waste when deliveries to the MGR are interrupted. Additionally, consideration would

be given to how lag storage would be used to enable the MGR to facilitate co-disposal of defense wastes and co-emplacement of commercial and defense wastes. Also considered would be to what degree lag storage could be used to mitigate the thermal effect in the drifts of a substantial amount of fuel arriving at the repository within less than 10 years from the time it was discharged from the reactor core.

Consideration was given to using heavy-haul trucking of large transportation casks instead of a dedicated rail spur, as this would have an effect on the funding requirements. This alternative evaluates rearranging the Viability Assessment design repository and storage facility design layouts so that sections of the facility can be built in lower-cost increments with minimal operational interruptions. By varying the timing and rates of operation, constrained funding may also be accommodated. This alternative considers modifications to the planned receipt and emplacement schedules and use of storage, allowing receipt faster and earlier than disposal, rather than emplacement of waste as fast as it is received (3,000 metric tons per year by the fifth year of operation).

The dry transfer system design (DOE 1996a) was investigated for use at either the generic interim storage facility or the repository. The study evaluates upgrades necessary to meet interim storage facility topical safety analysis report generic site environmental conditions, enhancements that are needed for improved throughput and handling capabilities, and enhancements required for integration with the interim storage facility or the repository (Heath 1998).

Another evaluation explored the early receipt of spent nuclear fuel at the potential repository (CRWMS M&O 1998c, p. ix). The study evaluates two licensing strategies and two facility types (integrated and co-located) within each strategy. An early receipt facility could be licensed under 10 CFR 72 for storage and under 10 CFR 60 for emplacement, or all licensing activities could be conducted in accordance with a revised 10 CFR 60 to allow early receipt of waste prior to the receipt of a license to begin disposal. Facility construction would be phased, with a module applicable to early receipt constructed in the first phase. This includes receipt of waste prior to 2010 in accordance with a revised 10 CFR 60, with no legislated interim storage. Also evaluated is interim storage in accordance with 10 CFR 72, with legislated interim storage enacted.

The Waste Handling System Design Drivers Study (an ongoing study) evaluates waste forms different from those assumed in the Viability Assessment (DOE 1998b). This study investigated program benefits to be derived if the waste forms and shipping casks are simplified from those assumed as the basis for the Viability Assessment design. The results of the study will serve as an input to the formulation of assumptions for the design basis waste stream study. Three simplifications will be considered:

Transportation and Disposal Canister System—Fuel assemblies would be loaded into large- or medium-sized disposal canisters. The canister baskets would be designed to satisfy disposal criticality and heat transfer requirements, as well as transportation requirements. The canisters would be shipped to the repository, where they would be placed into disposal containers and then be emplaced underground. The impacts of shipping all fuel in this manner will be estimated.

Uncanistered Spent Nuclear Fuel—The impacts of shipping commercial spent nuclear fuel as uncanistered fuel assemblies will be estimated.

Transportation Cask Standardization—The impacts of standardizing various aspects of shipping casks in order to simplify waste handling operations at the repository will be estimated. The analysis will consider standardization of envelope dimensions, interface features, and capacities. Standardized capacities will be assumed to be equal to capacities of disposal containers. Evaluation of the waste stream costs was performed (CRWMS M&O 1993g). The purpose of this study is to identify throughput rates and corresponding waste stream options that, if used, would result in lower waste handling systems construction costs. The study estimates cost reductions that could be achieved and penalties that would be incurred in comparison to the design for the current design-basis waste stream. Characteristics of the design-basis waste stream include peak receipt rates for storage and transportation canisters, and for high-level radioactive waste canisters, as well as the throughput levels (3,000 MTHM per year commercial spent nuclear fuel) specified by the Civilian Radioactive Waste Management System requirements document (DOE 1999). This study also examines the impact of the results of the design driver evaluation on the sensitivity of waste handling system costs to changes in throughput rates. The results of the study will help formulate assumptions for the design-basis waste stream study.

Other miscellaneous evaluations of alternative operations concepts underway are funding modes and waste receipt scenarios. These are described as follows:

Regional Transportation Analyses—These analyses will support various studies by providing the underlying design, cost, operations concepts, and schedules for transportation scenarios.

Parametric and Contingency Planning Study—This new parametric study will develop program options for several specific funding scenarios to evaluate the functions, construction schedule, and technical requirements that can be supported under each funding scenario.

Analysis Rapid Response Tool—This effort will develop a database and computer algorithms to be used for rapid development of cost and schedule data, which can be used to answer questions. Use of the tool is to be managed to ensure validity and consistency of cost and schedule data.

Cost Model and Total System Repository Life Cycle Cost—This task will produce an automated tool to provide updates to the estimate of the program repository life cycle cost; it will be used as the source for the repository life cycle cost for the program until the applicable report (CRWMS M&O 1995a) is revised.

Design-Basis Waste Streams—This activity provides scenarios that describe the flow of waste and shipping casks from the waste sites to the MGR. Each scenario is based on assumptions that provide a degree of conservatism to the characteristics of the waste and the shipping casks, as well as the rates at which the wastes will be picked up. The assumptions may also include the results and recommendations of the Waste Handling System Design Drivers Study (an ongoing study) and the report on Waste Handling Building material throughput (CRWMS M&O 1993g). The results of the analysis will be presented to the Office of Civilian Radioactive Waste Management. Office of Civilian Radioactive Waste Management decisions will be requested in

order to establish the basis for assumptions used to formulate: 1) the design basis waste streams for use by facility designers, and 2) the scenarios to be used for predictions of the program repository life cycle costs. The design basis waste stream will be described by several scenarios so that the Civilian Radioactive Waste Management System design will have the flexibility to support a variety of requests by the utilities.

DOE Spent Nuclear Fuel Handling Trade-Off—This study will determine if improvements can be made to the current approach for handling DOE spent nuclear fuel canisters in the Waste Handling Building; this study may have implications on the handling of spent nuclear fuel and on other areas of the Waste Handling Building.

NRC Issues (KTIs and Disruptive Events)

The purpose of this section is to show which of the NRC KTIs and disruptive events are considered in the EDA evaluation criteria described in Section 5.2. Those issues or events not considered in the evaluation criteria are also discussed here to indicate how they can potentially affect the selection of EDAs.

The NRC KTIs are identified (DOE 1998b, Vol. 3, p. A-24) as: 1) support revision of the U.S. Environmental Protection Agency standard/NRC rule-making, 2) total system performance assessment (TSPA) and technical integration, 3) igneous activity, 4) unsaturated and saturated flow under isothermal conditions, 5) thermal effects on flow, 6) container life and source term, 7) structural deformation and seismicity, 8) evolution of near-field environment, 9) radionuclide transport, and 10) repository design and thermal-mechanical effects.

Disruptive events considered for TSPA are basaltic igneous activity, seismic activity, nuclear criticality, and inadvertent human intrusion (DOE 1998b, Vol. 3, Section 4.4). Disruptive events have probabilities of less than 1 (i.e., their chances of occurring are less than 100 percent over the life of the repository), in contrast to expected events and processes (e.g., waste package corrosion, thermal effects, and groundwater flow and transport). Generally, disruptive events are rare (e.g., volcanoes or earthquakes), and have identifiable starting and ending times. Although criticality does not have a sudden onset, it is included here as an example of an off-normal condition.

The KTI referred to as support revision of the U.S. Environmental Protection Agency standard/NRC rule-making is not considered in the EDA design criteria.

The KTIs of TSPA and integration and radionuclide transport are directly related to the prediction of the transport of radionuclides to the accessible environment and are considered in the evaluation criteria in the screening criteria for postclosure performance and performance demonstrability.

The KTI of igneous activity pertains to the probability of igneous activity, the definition of this activity, the determination of recurrence rates and geologic factors that control the timing and location of igneous activity, and consequences of igneous activity within the repository setting. This KTI is considered as a disruptive event and is considered in the flexibility evaluation criteria where unanticipated natural features and findings (i.e., volcanism, seismicity, water table rise, flooding) are evaluated.

The KTI of unsaturated and saturated flow under isothermal conditions pertains to spatial distribution of present-day shallow groundwater infiltration, the estimated amount of infiltration and percolation through the repository, and the ambient flow conditions in the saturated zone. This KTI is considered in the evaluation criteria because it relates to the uncertainties associated with predicting postclosure performance.

The KTI of thermal effects on flow pertains to the potential for thermal reflux(ing) in the near field, the prediction of the nature and bounds of the thermal effects in the near field, and the adequacy of the TSPA (model) to account for thermal effects. All of these issues pertain to uncertainties in predicting the transport of radionuclides in water. Again, this KTI is considered in the evaluation criteria in the screening criteria of the prediction of postclosure performance and the performance demonstrability criteria.

The KTI of container life and source term pertains to the effects of corrosion of the waste package and release of radionuclides, material stability and mechanical failure, the resistance of the spent nuclear fuel (form) to degradation and release of radionuclides, and the resistance of high-level radioactive waste glass to the release of radionuclides. These issues relate to the time of release of radionuclides, and the source strength of the subsequent release. Thus, these effects relate to the performance of repository with respect to radionuclide transport. This KTI is considered in the evaluation criteria, in the screening criteria of the prediction of postclosure performance, and in the performance demonstrability criteria.

The KTI of structural deformation and seismicity pertains to the effects of fault slip, seismic motion, fractures and site discontinuities, and tectonics and crustal conditions. A portion of this KTI is considered in the flexibility evaluation criteria, which considers the two disruptive events of basaltic igneous intrusion (i.e., volcano) and seismic activity (i.e., earthquake). The fractures and site discontinuities are considered in the evaluation criteria, since these topics relate to uncertainties in the prediction of postclosure performance relative to the ingress of water into the repository.

The KTI of evolution of the near-field environment pertains to the effects of coupled processes on seepage (into the repository), waste package lifetime, rate of release of radionuclides, and the transport of radionuclides through engineered and natural barriers. This KTI is considered in the evaluation criteria, since it relates to uncertainties associated with predicting postclosure performance and is considered in the evaluation criteria.

The KTI of repository design and thermal-mechanical effects pertains to the effects of seismic events and fault disruption (waste package damage), thermal-mechanical effects on performance and changes in hydrological properties that may influence the near-field environment, and the performance of repository seals as related to the inflow of water and release of radionuclides. This KTI is considered in the evaluation criteria because it relates to the uncertainties associated with predicting postclosure performance. It is also included in the flexibility evaluation criteria where unanticipated natural features or findings (e.g., volcanism, seismic activity, water table rise, and flooding) are to be evaluated. The flexibility evaluation criteria thus considers two disruptive events: 1) basaltic igneous intrusion (i.e., volcano) and 2) seismic activity (i.e., earthquake).

The disruptive events not considered in the KTIs or the EDA evaluation criteria are nuclear criticality, criticality in the near field environment, and inadvertent human intrusion. These disruptive events have recently been discussed (DOE 1998b) and are summarized here with differences between the TSPA-Viability Assessment model (DOE 1998b, Vol. 3) and the EDAs noted.

Isolated nuclear criticality events could occur if the engineered control measures in the waste package fail and other conditions occur, such as the presence of water. Additionally, fissile material in the waste can potentially form a critical configuration in the surrounding rock. Although criticality is very unlikely because multiple failures in designs and materials must occur, it cannot be ruled out during the period of repository performance. Criticality can occur in two locations in a repository system: inside a waste package, or in the surrounding rock. A summary of the physical and chemical processes that act to make a repository criticality an unlikely event (either inside or outside the waste package) follows.

Most of the waste packages cannot go critical, because they do not have sufficient fissile material to form a critical mass (DOE 1998b, Vol. 3, p. 4-99). Of waste packages that potentially could have sufficient fissile material for criticality, most will be commercial spent nuclear fuel waste packages. Spent nuclear fuel packages that could potentially contain sufficient fissile material will decrease by 30 percent for times beyond 40,000 years (DOE 1998b, Vol. 3, p. 4-99). This significantly decreases the possibility of a criticality, because it is anticipated that a small number of waste packages will be breached by 40,000 years (DOE 1998b, Vol. 3, p. 4-99). Of the waste packages that could potentially contain sufficient fissile material for criticality once they are breached and degraded, most require some form of water retention to provide moderation. Models of the TSPA-Viability Assessment (DOE 1998b, Vol. 3) waste package corrosion indicate that only a small percentage of the breached waste packages would hold significant amounts of water for the time required to flush the neutron absorbers that have been added for criticality prevention.

External criticalities are considered extremely unlikely because of the low probability of accumulating significant amounts of fissile material by any credible geologic process. Since the information summarized in this paragraph is from the TSPA-Viability Assessment model (DOE 1998b, Vol. 3), where a waste package containing 21 pressurized-water reactor design basis fuel assemblies is considered, and the EDAs are based on a 21 pressurized-water reactor waste package or smaller, a nuclear criticality in the repository for the EDAs is considered an unlikely event at this time. However, since the waste package materials for the EDAs under consideration are expected to change from those used in the TSPA-Viability Assessment model (DOE 1998b, Vol. 3), a re-analysis of some aspects of nuclear criticality will have to be conducted in the future. Specifically, the topic of holding water in a larger number of waste packages because of reduced corrosion rates will have to be considered with respect to flushing, or removing, the neutron absorber material.

A National Academy of Sciences panel (National Research Council 1995) concluded that it is not possible to make scientifically supportable predictions of the probability of human intrusion breaching the repository's geologic or engineered barriers over a period of 10,000 years. While the National Academy of Science panel report recommended that human intrusion be excluded from the performance assessment for the repository, it also recommended that the consequences

of the assumed human intrusion scenario be calculated to determine if the repository performance would be degraded substantially as a result of the intrusion. To permit such consideration of the impacts of a human intrusion scenario in the evaluation of the postclosure performance of a repository at Yucca Mountain, the NRC has proposed (see 64 FR 8640, p. 8677) that DOE be required to perform a consequence analysis that includes an assumed intrusion scenario. The NRC has proposed a scenario that would result in the breach of both the engineered and the geologic barriers. When subjected to this assumed scenario, the repository is required to perform such that the expected annual dose to the average member of the critical group is also within the allowable limits for the repository.

APPENDIX D
GLOSSARY

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GLOSSARY

Accessible Environment—This term refers to the atmosphere, the land surface, surface water, and oceans that humans may contact. This term is also used for the area surrounding a nuclear waste disposal site.

Aging—An operational tool that takes advantage of the natural decay of radionuclides, resulting in the decrease in heat output of waste forms prior to repository closure.

Alloy-22—A metal that contains a high amount of nickel combined with molybdenum, tungsten, and iron. Alloy-22 is extremely corrosion-resistant in both oxidizing and reducing environments, and is particularly resistant to localized (pitting and crevice) corrosion when tested in the as-welded condition.

Alluvium—Alluvium is sedimentary material deposited by flowing water or by wind and includes clay, mud, sand, silt, and gravel.

Areal Mass Loading—A measure of the average amount of waste per unit area in the repository footprint. The units for areal mass loading are metric tons of heavy metal per acre.

Blast Cooling—Temporary use of high-flow ventilation in specific emplacement drifts to lower the drift temperature for a specific time and purpose.

Blending (Thermal Blending)—Refers to the systematic, deliberate selection of spent nuclear fuel assemblies to be placed with one another within a particular waste package, as compared with a random or “as received” order of filling the waste packages. Blending can be performed to reduce the heat output variability (thermal blending) of the waste packages or to reduce the reactivity of the waste packages (blending for criticality control).

Boiling Front—The region in the rock surrounding an emplacement drift that marks the threshold between rock temperature above the boiling temperature of water and rock temperature at or below the boiling temperature of water.

Central Estimate—A calculated value arrived at by performing a single realization using a single value of most variables in the total system performance assessment model.

Cladding (Fuel Cladding)—Cylinders of metal surrounding and containing the fuel pellets in a U.S. Department of Energy or commercial spent nuclear fuel assembly. These cylinders, closed on each end, are made of a zirconium/steel alloy (Zircaloy®), or in a small percentage of cases, stainless steel. The fuel cladding is intended to isolate the fuel from the external environment.

Commercial Spent Nuclear Fuel—Fuel that has been removed from a commercial nuclear reactor following irradiation and power production. The radionuclides in the fuel have not been separated by any reprocessing activity. The fuel is more radioactive than it was prior to irradiation, and is also a continuing heat source.

Critical/Nuclear Criticality—This is a condition in which nuclear fuel sustains a chain reaction of fission events. It occurs whenever the number of neutrons in one generation cycle is equal to the number of neutrons in the previous cycle, excluding source neutrons (neutrons resulting from decay or spontaneous fission of nuclides).

Defense in Depth—This term is used to describe the property of any system of multiple barriers designed to mitigate unanticipated conditions, processes, and events so that failure in any one barrier does not result in failure of the entire system.

Derating—The loading of fewer than the maximum number of spent nuclear fuel assemblies in a particular waste package, for the purpose of lowering the waste package heat output and/or criticality potential. Non-fuel space fillers would occupy the spaces not loaded with spent nuclear fuel assemblies.

Design Alternative—Each design alternative (DA) represents a fundamentally different conceptual design for the repository and, potentially, could stand alone as the License Application repository design concept. DAs are distinguished from design features (DFs) by their complexity and the number of attributes involved. DAs, while not mutually exclusive, represent diverse and independent methods of accomplishing the repository mission—safe disposal of spent nuclear fuel and high-level radioactive waste. One example of a DA is a repository designed to use continuous natural ventilation to remove heat and moisture from the area of the waste packages after the repository has been closed.

Design Basis Event—A natural or human induced event that may occur before permanent closure of the geologic repository's operations area.

Design Feature—A DF is a particular element or attribute of the repository that could be added to a DA to enhance its performance. An individual DF may represent a discrete concept, such as use of shielded waste packages, or a continuous range of values of some aspect of repository design, such as spacing of the waste emplacement drifts. DFs can be added to any DA singly or in combination, although the compatibility of different DAs and DFs vary.

Design Margin—This term refers to the difference between a design requirement and exceeding that requirement to provide a margin of safety.

Design Trade—There are two types of design trades. One is performed within a DF to evaluate the variations of the attributes of the features; the second is performed external to the License Application Design Selection project, because it involves repository attributes that do not directly affect postclosure performance.

In the first type of design trade, a particular DF may have within it a variety of implementations that would meet the definition of an individual DF. These implementations might include concepts such as different materials or configurations, or they might include different values of parameters such as length, temperature, or weight. These differences are considered variations within a DF and are designated design trades. These are subsets of the DF and are evaluated as part of the DF. The evaluation identifies which variation of the DF is most likely to enhance the postclosure performance of the particular DA with which it has been combined. For example, an evaluation might compare cast-in-place concrete to precast concrete, metal ground support to no

ground support, 5.5 m drift diameter to 4.3 m drift diameter, or waste package corrosion-resistant material as an inside barrier to waste package corrosion-resistant material as an outside barrier.

The second type of design trade might compare rail to gantry for waste package emplacement, or wet handling to dry handling for waste packaging.

Disruptive Event—An unexpected event that has a probability less than one over the life of the repository and has identifiable starting and ending times. Igneous activity, seismic activity, inadvertent human intrusion, and nuclear criticality are disruptive events that may impact performance.

Drift—Drift is a mining term and means a horizontal underground passage that runs from the shaft(s) to the alcoves and room(s). It includes excavations for emplacement (emplacement drifts) and access (access mains).

Drift Spacing—The distance between parallel emplacement drifts, measured from the drift centerlines.

Drip Shield—A drip shield is a sheet of impermeable material placed above the waste package to prevent seepage water from directly contacting the waste package.

Enhanced Design Alternative—Enhanced design alternatives (EDAs) are combinations of one or more DAs and DFs that fit logical principles derived from the objectives for repository design. EDAs selected for evaluation are those combinations that include mutually compatible attributes and expected postclosure performance characteristics that exceed those of the basic DAs. Other characteristics considered in developing the EDAs include the compatibility of the DAs and DFs; the developmental, operational, and maintenance simplicity of the resulting combination; and the ability of the set of EDAs to address the entire set of DAs and DFs.

Getter—Any material with a high affinity for sorbing radionuclides.

High-Level Radioactive Waste—(1) Radioactive material resulting from reprocessing of spent nuclear fuel, liquid waste produced directly in reprocessing, and solid material derived from such liquid waste that contains fission products in sufficient concentrations to require permanent isolation. (2) Other highly radioactive material that the U.S. Nuclear Regulatory Commission, consistent with existing law, determines by rule to require permanent isolation.

Juvenile Failure—Early failure resulting from manufacturing or operational defects.

Line Load/Point Load (Waste Package Spacing)—Two distinctly different emplacement strategies for waste packages within a drift. Line load refers to placement such that the waste packages are virtually end-to-end or nearly touching. Point load refers to placement such that the waste packages are separated by at least 2 m (see Figure 4-25).

Metal Alloy Nomenclature—Nomenclature for various alloys used in this report are summarized in Table D-1.

Table D-1. Metal Alloy Nomenclature

Name	Common Term	ASTM/ASME	UNS Number
Carbon Steel	A516	SA-516	K02700
Alloy-22	A22	SB-575	N06022
Stainless Steel	316L	SA-240	S31603
Titanium Alloy Grade 7	Ti-7	SB-265	R52400

mrem (millirem)—Rem is the acronym for roentgen-equivalent-man. The rem is a unit used to derive a quantity called equivalent dose. This relates the absorbed dose in human tissue to the effective biological effects of the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Equivalent dose is often expressed in terms of thousandths of a rem, or mrem. To determine equivalent dose (rem), multiply absorbed dose (rad) by a quality factor (Q) that is unique to the type of incident radiation.

Natural Ventilation Pressure—The pressure differential between warmer air heated by waste decay and cooler surrounding air. It is the driving force of unpowered ventilation.

Near Field—The region where the adjacent natural geohydrologic system has been significantly impacted by the excavation of the repository and then emplacement of the waste.

Neutralization—An artificial calculational assumption that a principal barrier does not perform its anticipated postclosure containment and/or isolation function. Neutralization is used to gain insight into the relative contribution that different barriers make to total repository performance.

Off-Normal Event—An unexpected event taking place during normal operations (e.g., equipment malfunctions).

One-Off—A single change from the Viability Assessment.

Performance Assessment—An analysis that predicts the behavior of a system or system component under a given set of constant and/or transient conditions.

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

Performance Margin—The ratio between the calculated dose rate and the screening criterion of 25 mrem/yr.

Pillar—The region of rock between the emplacement drifts.

Pit Repassivation—An electrochemical process by which a protective oxide layer is formed over a pit or crevice in a corrosion-resistant material. The formation of this oxide layer terminates the growth of the pit or crevice, stifling the localized corrosion.

Principal Barrier—Any barrier that either delays the release of radionuclides to the environment by more than 1,000 years or reduces the radionuclide concentration in the environment by a factor greater than 10^4 .

Radionuclides—Atoms that disintegrate by the emission of corpuscular or electromagnetic radiation (e.g., alpha, beta, gamma, or neutron radiation).

Reflux or Refluxing—The return flow of water (by gravity) after water has been vaporized (boiled) and transported to the cooler region above the drift. The reflux flow begins when the vapor condenses in the cooler rock above the drift, and returns back toward the hotter rock.

Rock Bolt—A bar, usually constructed of steel, that is anchored into predrilled holes in rock as a support or reinforcement device. The term also refers to the method of ground support using such devices to support walls and ceilings in underground excavations.

Saturated Zone—The region below the water table where rock pores and fractures are completely saturated with groundwater.

Shedding—The forced movement of water around a drift. The forcing movement occurs by allowing the rock temperature close to the drift to exceed the boiling point of water. The region between the drifts (see definition for **pillar**) remains below the boiling point of water, allowing water to flow by gravity around the drifts.

Spalling—Severe form of flaking of materials, especially with layered materials. The spalling could be caused by an expansive action of the corrosion products as they occupy a greater volume than the uncorroded metal substrate.

Steel Sets—Steel tunnel supports used in the main entries of mines and shafts. The sections are I-beams for caps and H-beams for posts or wall plates. The H-beams give equal stiffness in two directions at right angles to each other.

Thermal Period (Thermal Pulse)—The time during which the waste packages emit a significant amount of heat. This is the time period when the thermal processes could be coupled, and in which the waste package material could be affected by thermally induced localized corrosion. This would end when drift temperatures cooled below 50°C.

Timing Figure of Merit—The purpose of the timing figure of merit is to provide a measure of the shape of the dose rate curve (as a function of time). An integral of the dose rate with respect to time would not do this because a large dose rate, or a peak in the dose rate, occurring early in time would not be distinguishable from one occurring much later because the area under these two dose rate curves would be the same. Therefore, the integrand is the dose rate divided by time to provide an inverse weighting of the dose rate curve at later times. This now provides a way to distinguish early peaks in the dose rate curve relative to those peaks that occur later. Also, it is desirable to weight dose rate information for later times less than data for early times

because later occurring information is proportionally more uncertain. The lead constant that multiplies the integral yields a unit timing figure of merit for the case of unit dose rate from 1,000 years to 1 million years (and zero before 1,000 years). The units for the timing figure of merit are dose rate.

Tuff—Igneous rock from compacted volcanic fragments from explosively ejected flows with particles generally smaller than 4 mm in diameter. This is the most abundant type of rock at the Yucca Mountain site.

Unsaturated Zone—Soil or rock below the ground surface and above the water table in which the pore spaces contain water, air, and other gases. Generally, the water saturation is below 100 percent in this zone.

Viability Assessment Design—The repository design concept presented in the *Viability Assessment of a Repository at Yucca Mountain* (DOE 1998b).

Vitrified/Vitrification—A type of processed high-level radioactive waste where the waste is mixed in a liquid form with glass-forming chemicals and put through a drying and melting process. The melted mixture is then put into a canister where it becomes a dry “log” of waste in a glassy matrix.