SANDIA REPORT

SAND91—0025/2 • UC—814
Unlimited Release
Printed September 1991

Yucca Mountain Site Characterization Project

Exploratory Studies Facility Alternatives Study: Final Report

Volume 2: A Comparative Evaluation of Alternative Exploratory Studies Facility Options

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for the United States Department of Energy
under Contract DE-AC04-76DP00789

→ Part 1

"Prepared by Yucca Mountain Site Characterization Project (YMSCP) participants as part of the Civilian Radioactive Waste Management Program (CRWM). The YMSCP is managed by the Yucca Mountain Project Office of the U.S. Department of Energy, Nevada Operations Office (DOE/NV). YMSCP work is sponsored by the Office of Geologic Repositories (OGR) of the DOE Office of Civilian Radioactive Waste Management (OCRWM)."

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NTIS price codes
Printed copy: A20
Microfiche copy: A01

SAND91-0025

EXPLORATORY STUDIES FACILITY ALTERNATIVES STUDY FINAL REPORT

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ABSTRACT

An Exploratory Studies Facility (ESF) is planned for use in the characterization of a potential site for a high-level nuclear waste repository at Yucca Mountain, NV. A comparative evaluation of ESF-repository design options was conducted for the Department of Energy's Yucca Mountain Site Characterization Project Office. The purposes of the evaluation were to identify and rank order ESF-repository options and to improve understanding of the favorable or unfavorable features of an ESF design. The evaluation relied on techniques from decision analysis, including decision trees and multiattribute utility analysis (MUA). Decision trees provided a means for evaluating decisions under uncertainty. MUA provided a means for evaluating decisions with multiple, possibly competing objectives. Thirty-four ESF-repository options were evaluated and ranked based on inputs provided by 11 panels composed of technical specialists and one panel composed of senior managers. With guidance from decision analysts, the technical specialists developed the measures for quantifying performance; identified, developed, and analyzed scenarios for the development and operation of the ESF and the potential repository; and provided estimates of the probabilities of uncertainties and the performance of each option against various performance measures. With similar guidance, the senior managers specified the objectives and criteria for the evaluation, the value tradeoffs among objectives, and the attitude toward risk used in the analysis.

This work was performed under the Sandia National Laboratories Nuclear Waste Repository Technology Department Quality Assurance Plan as a quality-affecting activity. Records associated with this activity have been filed under the following headings:

WBS 1.2.6.1.1

Interaction Task Memorandum (ITM) 010

Design Investigation Memo 240, Development of a Decision Methodology for the ESF Alternatives Study

Design Investigation Memo 241, Selection of Evaluation Panel Members

Design Investigation Memo 242, Development of Preliminary Screening

Design Investigation Memo 243, Identification of Repository Access and ESF Options

Design Investigation Memo 244, Identification of Repository and ESF Design, Performance and Construction Requirements

Design Investigation Memo 245, Development of Influence Diagrams and Performance Measures for the ESF Alternatives Study

Design Investigation Memo 246, Exploratory Shaft Facility (ESF) Alternatives Evaluation Study - Task 7 Subtask-Testing

Design Investigation Memo 249, ESF Alternatives Study Task 1. Plan Management

Design Investigation Memo 250, ESF Alternatives Study Task 6. Final Report

Design Investigation Memo 251, Evaluation of Repository/ESF-Feature Performance Discriminators

Design Investigation Memo 252, Application of Management and Policy-Based Judgments to the ESF Alternatives Study

Design Investigation Memo 254, Scoring of Options for the ESF Alternatives Study

ACKNOWLEDGMENTS

We would like to express our appreciation to Al Stevens and Earl Gruer of Sandia's Repository Engineering Division who, respectively, provided overall direction to the study and led the options development task, and to Steve Bauer of Sandia's Geomechanics Analysis and Testing Division who led the evaluation task.

Thanks to Ned Elkins of Los Alamos National Laboratory for his coordination of the ESF testing activities with the facility design activities, and to Bill Kennedy of Raytheon Services Nevada and Brian Lawrence of Parsons Brinckerhoff Quade & Douglas who explained the features of the many options to members of the expert panels.

Also, our thanks to the following individuals who made significant contributions to the work reported in the Exploratory Studies Facility Alternatives Study Final Report.

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VOLUME 2

A COMPARATIVE EVALUATION OF ALTERNATIVE EXPLORATORY STUDIES FACILITY OPTIONS

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1.0 INTRODUCTION

1.1 Description of the Study

The Department of Energy (DOE) has the responsibility for developing a mined geologic repository[1] for the disposal of spent nuclear fuel and other high-level radioactive waste. A site at Yucca Mountain Nevada has been tentatively identified as a possible location for a repository. If a repository is built at Yucca Mountain, it will consist of a system of tunnels and rooms excavated in rock formations approximately 300 meters below the surface. After waste has been placed in the repository rooms, called emplacement drifts, and the performance of the repository has been confirmed according to applicable regulatory requirements, the repository openings will be permanently sealed and the facility will be officially decommissioned.

A multiyear research program termed "site characterization" is to be conducted to investigate whether the proposed Yucca Mountain site is a suitable location for the repository. A critical decision for the characterization program is the selection of a design -- including a location, construction method, and testing strategy -- for the underground test facility central to the effort. This facility is known as the Exploratory Studies Facility (ESF).[2]

To assist the DOE in selecting an ESF design, the DOE's Yucca Mountain Site Characterization Project Office (YMPO) asked Sandia National Laboratories (SNL) to provide the department's Office of Civilian Radioactive Waste Management (OCRWM) with the information it required to make an informed decision regarding the selection of a preferred configuration for an ESF at Yucca Mountain, NV. It is the YMPO's intention to use the configuration selected by the OCRWM as a basis for the design of the ESF. The scope of the ESF-AS was to obtain this information by

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[1] The term "repository" appears throughout Volumes 1 and 2 and the appendices of this document. The use of the term "repository" to identify the facility that may be constructed and operated at Yucca Mountain is not intended to imply that such a facility will be constructed or operated at this site.

[2] In March 1991, the name of the underground exploration facility at Yucca Mountain was changed from Exploratory Shaft Facility to Exploratory Studies Facility. The new name will be used throughout this document, but documents generated prior to April 1, 1991 will not be revised to change the facility name. Thus the names Exploratory Shaft Facility and Exploratory Studies Facility have the same meaning in all supporting materials for this study.

identifying alternative ESF configurations and comparatively evaluating these alternative configurations. The goals of the comparative evaluation were to (1) establish an ordered preference list by rank ordering the options under consideration, and (2) identify individual features contained in some options that, if incorporated in other options, could be expected to improve the rank of the other options.

It was recognized that the results of the study might or might not confirm the design recommended in the Site Characterization Plan (SCP) (DOE, 1988). Thus, the study was envisioned to either (1) provide convincing evidence that the SCP ESF design was appropriate or (2) provide a basis for developing an alternative ESF design. The optimization of ESF configurations to achieve specific goals was not within the scope of this study; however, optimization of the ESF configuration can be addressed by the facility designer during the Title II phase of the ESF design.

The major elements of the study and their relationships are illustrated in Figure 1-1. These study elements include: (1) generating and screening alternative ESF-repository options, (2) identifying requirements and concerns, (3) developing and testing a methodology for evaluating and comparing options, (4) applying the methodology to obtain a comparative evaluation of candidate options, and (5) developing study findings.

This document is the second volume of a two-volume report summarizing the Exploratory Studies Facility Alternatives Study (ESF-AS). Volume 1 contains an Executive Summary of the full study, provides a description of the options evaluated, identifies regulatory requirements and concerns that discriminate among options, analyzes principal factors and features, and summarizes overall study conclusions. This volume, Volume 2, documents the comparative evaluation of candidate Exploratory Study Facility-repository (ESF-repository) options that provided the nucleus for the study. It summarizes the methodology used, describes the results of the comparative evaluation, and presents insights and conclusions.

1.2 Motivation for Study

In December 1988, DOE published a SCP for Yucca Mountain that included a recommended ESF design (DOE, 1988). The U.S. Nuclear Regulatory Commission

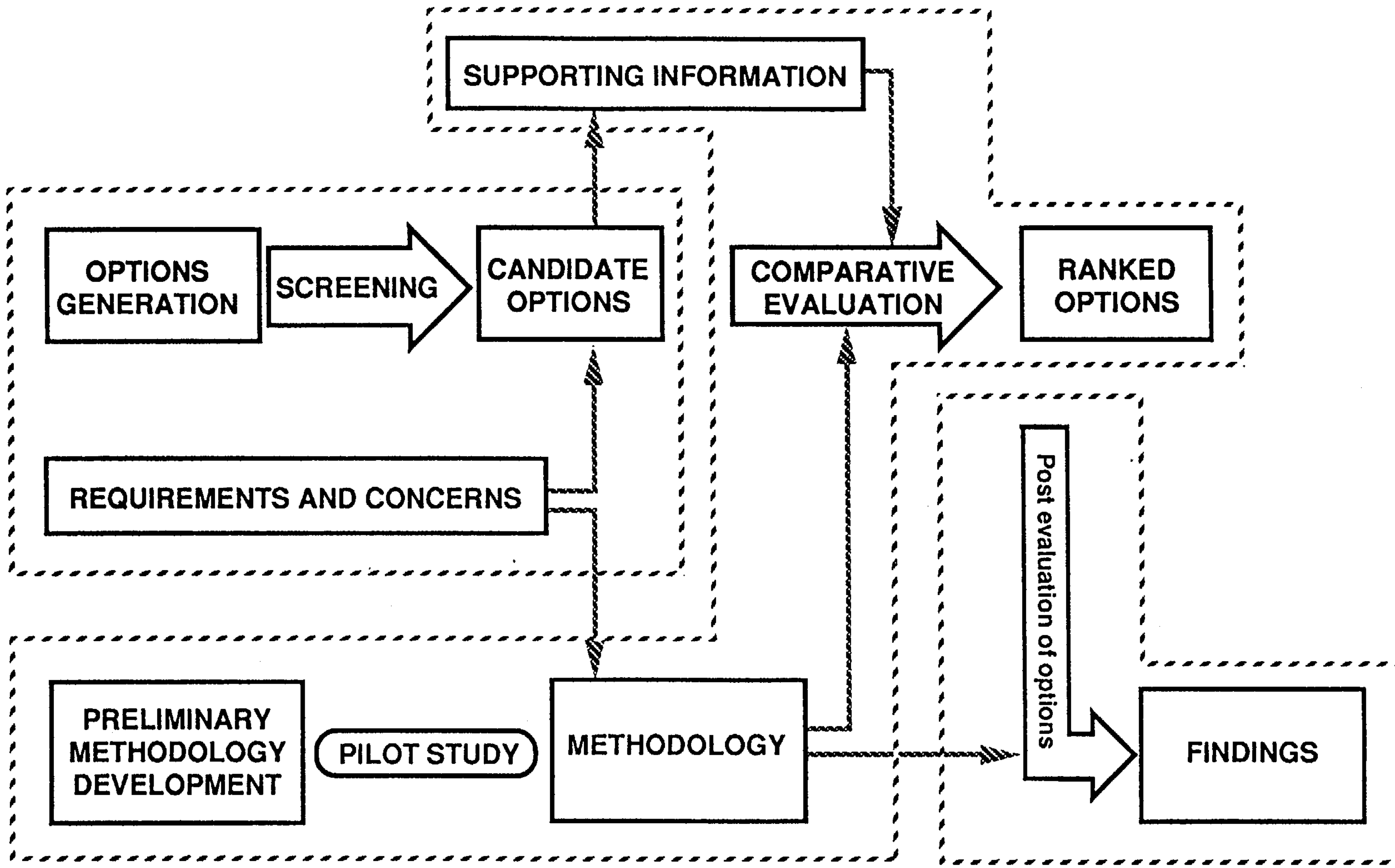

Figure 1-1. ESF Alternatives Study

(NRC), the agency that will ultimately be asked to grant a license to construct and operate the repository, objected to various features of the proposed ESF design and criticized DOE for failing to conduct a systematic evaluation of alternative designs (NRC, 1989). Concerns over the SCP ESF design were also expressed by the Nuclear Waste Technical Review Board (NWTRB), an independent oversight committee (NWTRB, 1989; NWTRB, 1990). Meanwhile, construction of the ESF was delayed when, in the fall of 1989, the DOE was unable to obtain the necessary permits for the continuation of the work. The OCRWM and the YMPO chose to use this delay to perform a single comprehensive analysis to address the NRC, State, and NWTRB concerns and suggestions. Thus, the ESF-AS was proposed by the DOE as a means of responding to the concerns expressed by the NRC, the State of Nevada, and the NWTRB, while making use of the delay in ESF construction.

1.3 Candidate ESF Options

Volume 1 of this report describes in detail the candidate options and the process by which these options were generated. Only a brief summary is provided here.

ESF and repository decisions are intimately connected. The goal of the exploratory studies is to conduct appropriate site characterization activities at the candidate site while insuring that the investigations to obtain the required information are conducted in such a manner that adverse effects on the long-term performance of any potential geologic repository that might be constructed and operated at that candidate site are limited (to the extent practical). Experience suggests that the interrelationship among various major features is such that if they were evaluated individually and then combined into a system, the system would not be an optimum system. For example, the optimum locations and type of accesses for a repository might not support the need to conduct appropriate site characterization activities. Conversely, access means and locations determined when considering only the ESF might not support the need to limit adverse effects (to the extent practical) on the long-term performance of any potential geologic repository that might be constructed and operated at that candidate site. Thus evaluation of configurations and construction methods should consider the ESF and the repository as a total system. To account for the close tie between the ESF and the subsequent repository, an option was defined to consist of an ESF configuration plus a specified, compatible repository configuration.[3]

The connection between the ESF and the subsequent repository means that choosing an ESF option requires making interdependent choices of five key types:

- Means of access -- How many ramps and/or shafts should be planned for repository development and operation, and which of these should be initially constructed for the development and operation of the ESF?

- Location of accesses -- Where should these accesses be located, taking into account functional and other requirements, including construction considerations, surface terrain, overburden, and performance requirements?

- Test area configuration -- What underground areas should be used for testing conducted as part of the ESF, including accesses, the main test level (MTL), and other drifts that might be constructed to explore specific geological features?

- Construction methods -- What methods should be used to construct the ESF and subsequent repository (e.g., conventional drill-and-blast methods, or machine excavation methods such as shaft-boring machine, blind hole drill, V-mole, or raised bore for shafts; tunnel boring machine (TBM), or road header for ramps)?

- ESF-repository interface -- In what manner should the ESF and repository be integrated -- for example, should ESF ramps or shafts be later used for repository materials handling, personnel, ventilation, or other repository functions?

[3] The tie between ESF and repository designs made for the purposes of the analysis should not be interpreted as implying a lack of flexibility for changing the repository design once the ESF option has been selected. On the contrary, the repository design may well be modified based on the results of characterization and other information. However, given that the same degree of flexibility exists regardless of the selected ESF design, and the fact that a large number of options were evaluated, the association of an ESF and compatible repository design was regarded as an appropriate formulation for the analysis.

The ESF-repository design recommended in the SCP provides one set of choices for the above decisions. An ESF-repository design similar to that recommended in the SCP was, therefore, designated as Option 1. Option 1 served as a convenient base case for comparison, because the design was well developed and familiar to Study participants.

Figure 1-2 is an isometric sketch illustrating the underground layout of Option 1. The option would rely on a total of six accesses. Two 12-foot-diameter shafts would provide access to the ESF. The ESF and repository would be mined predominantly by the drill-and-blast method. The MTL would be located in the northeast corner of the repository block at an elevation corresponding to that of the repository. The four additional accesses for the repository would include two TBM ramps for transporting mined tuff and radioactive waste. TBMs would also be used to mine the perimeter drifts and some of the main drifts. Two additional shafts would be mined to provide ventilation and transport of personnel and materials. In the ESF, exploratory drifts would be mined to intercept potentially important geologic features, including the Ghost Dance Fault, the Drill Hole Wash Fault, and imbricate faults.

To generate additional options for the analysis, historical and new ESF and repository concepts were considered. Historical options included previously developed concepts for the ESF and repository that were developed since 1980 but, while appearing to have merit, were not recommended in the SCP. A total of 52 historical ESF configurations and 15 historical repository configurations were identified. New options included several major revisions to the SCP-recommended design to address the various concerns raised by the NWTRB, NRC, and State of Nevada. Twenty-four preliminary new options were developed.

The initial options were screened, based on ability to meet regulatory and testing requirements, with the goal of identifying finalists with a diversity of choices for the five key design decisions listed above. A total of 17 finalists were so identified. This number was subsequently doubled to evaluate two alternative testing strategies. The result was 34 options, numbered 1 through 34, consisting of 17 Option Pairs (1 and 18, 2 and 19, . . . and 17 and 34), with each member of a pair having similar physical configurations and construction methods but different testing strategies.[4]

[4] In some cases (notably Option Pair 13 and 30), the configuration differed slightly to accommodate the implementation of different test strategies. Details of the development and screening of the options are presented in Sections 3, 4, and 5 of Volume 1 of this report.

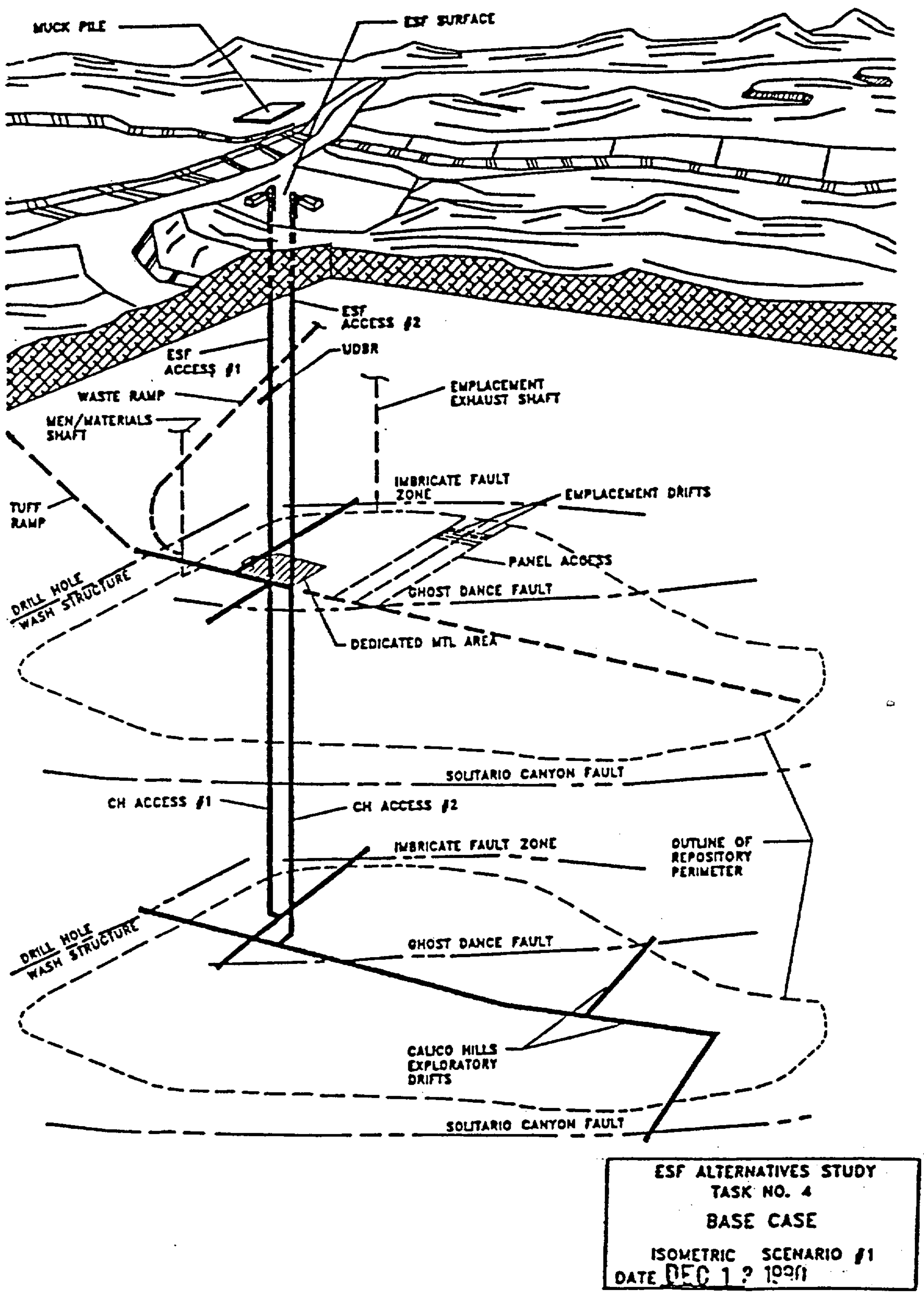

Figure 1-2. Underground Layout for Option 1 -- Base Case

Options 1 through 17 use the SCP-recommended test strategy. This test strategy is based on an orderly progression of construction and site characterization testing from the surface, down the accesses to the Topopah Spring (TS) unit, and then down to the Calico Hills (CH) unit. Testing in the CH unit could be conducted simultaneously with that in the TS unit if the option would support the activity. Options 18 through 34 use an alternative testing strategy based on proceeding as rapidly as possible to the CH unit to conduct an early investigation of the suitability of this principal natural barrier to the transport of waste. With this strategy, tests conducted in the accesses during construction are restricted to (1) those necessary to acquire site data that would be irrecoverable if not obtained during initial construction and (2) those that could be conducted without interfering with the construction schedule. Testing in the TS unit could be conducted simultaneously with that in the CH unit.

Table 1-1 summarizes the major features distinguishing the 17 option pairs. The table includes a secondary designation code for options, used to summarize the distinctions with regard to several of the key design choices listed above. This code was used by many members of the Study task force (see Volume 1, Section 3) and in the figures in this volume showing the underground layouts of options. With this code, each option is referred to by a letter that designates its key distinguishing features.

TABLE 1-1

MAJOR FEATURES DISTINGUISHING ESF-REPOSITORY OPTION PAIRS

Secondary Option Designation	Distinguishing Features
A	Conventional Repository Layout -- Drill-and-Blast Construction
B	Conventional Repository Layout -- Mechanical Excavation
C	Stepped Block Repository Layout -- Mechanical Excavation
R	Historical (Conventional) Repository Layout -- either Drill-and-Blast or Mechanical

Options using the conventional repository layout (A and B designations) incorporate a physical configuration similar to the base case and would be constructed on a single horizon. The stepped block repository design (C designation) would be developed on two horizons. One option pair in the final set of 34 options (R designation) was a historical repository configuration using mechanical mining methods.

As summarized in Table 1-2, at least one ESF shaft access is used in the designs for all options, except for the two Option Pairs, 6 and 23 and 13 and 30, which rely entirely on ramps for the ESF. For most options, the MTL would be located in the northeast. However, the MTL would be located in the south of the repository block in five option pairs, one of which uses the conventional repository layout mined using drill-and-blast methods (Option Pair 5 and 22, 13 and 30, and 14 and 31), three of which use the conventional repository layout with mechanical excavation methods (Option Pairs 12 and 29,13 and 30, and 14 and 31), and one of which uses a stepped block layout (Option Pair 16 and 33).

1.4 **Requirements Governing the Choice of Comparative Evaluation Methodology**

The selection of the method for evaluating and comparing candidate options was a particularly important decision for the ESF-AS, in part because of the early criticisms of the SCP ESF design but also because deciding among ESF options presents several important difficulties. A successful study required a method of analysis that would be effective in addressing these difficulties.

- The first difficulty in choosing an option is that each feature of an option typically has both positive and negative implications. For example, a design with a relatively large number of accesses tends to expose more rock, which might be useful for testing. On the other hand, a design that involves much excavation might be more costly and produce more adverse impacts on the natural environment. Selecting an option under these circumstances requires considering multiple, sometimes competing objectives. An evaluation methodology capable of accounting for multiple objectives was, therefore, required.

- Second, the actual performance of an option cannot be precisely predicted at this time, because repository performance characteristics and many features of the Yucca Mountain site are uncertain. Indeed, the primary function of the characterization program is to reduce uncertainty. An evaluation methodology capable of dealing with uncertainty was, therefore, required.

TABLE 1-2

SUMMARY OF ESF/REPOSITORY OPTIONS

OPTION #			ESF								REPOSITORY				
			ACCESS-1		ACCESS-2		MAIN TEST LEVEL				ACCESSES		CONSTRUCTION METHOD		
			SIZE	CONST. METHOD	SIZE	CONST. METHOD	LAYOUT	CONST. METHOD	LOCATION	ELE-VATION	SHAFTS	RAMPS (TBM)	RAMPS & DRIFTS	EMPL. AREA	TOTAL ACCESSES
1	18	BASE CASE	12' SHAFT	DRILL & BLAST	12' SHAFT	DRILL & BLAST	TITLE II G.A.	DRILL & BLAST	NE	SAME AS REPOS.	2 - 20'	1 - 25' 1 - 23'	TBM	DRILL & BLAST	6
2	19	A1	16' SHAFT	--- " ---	25' RAMP	TBM	MODIFIED T II G.A.	--- " ---	--- " ---	--- " ---	2 - 25'	1 - 25' + ESF	--- " ---	--- " ---	5
3	20	A2	16' SHAFT	--- " ---	16' SHAFT	DRILL & BLAST	--- " ---	--- " ---	--- " ---	--- " ---	--- " ---	2 - 25'	--- " ---	--- " ---	6
4	21	A4 REV. 1	16' SHAFT	--- " ---	12' SHAFT 25' RAMP	DRILL & BLAST TBM	--- " ---	--- " ---	--- " ---	--- " ---	1 - 25' ENLARGE ES - 2 25'	1 - 25' + ESF	--- " ---	--- " ---	5
5	22	A5	16' SHAFT	--- " ---	25' RAMP	TBM	--- " ---	--- " ---	S	--- " ---	2 - 25'	--- " ---	--- " ---	--- " ---	5
6	23	A7	25' RAMP	TBM	25' RAMP	--- " ---	--- " ---	--- " ---	NE	--- " ---	--- " ---	IN ESF	--- " ---	--- " ---	4
7	24	B3, REV. 2 —	16' SHAFT	· SBM	--- " ---	--- " ---	--- " ---	MECH.	--- " ---	--- " ---	--- " ---	1 - 25' + ESF	--- " ---	TBM	5
8	25	B3, REV. 3 —		· V-MOLE											
9	26	B3, REV. 4 —		· BLIND BORE											
10	27	B3, REV.5 —		· RAISE BORE											
11	28	B3, REV. 6 —		· DRILL/BLAST											
12	29	B4	16' SHAFT	DRILL & BLAST	--- " ---	--- " ---	--- " ---	--- " ---	S	--- " ---	--- " ---	--- " ---	--- " ---	--- " ---	5
13	30	B7	25' RAMP	TBM	--- " ---	--- " ---	--- " ---	--- " ---	--- " ---	--- " ---	--- " ---	IN ESF	--- " ---	--- " ---	4
14	31	B8	16' SHAFT	DRILL & BLAST	--- " ---	--- " ---	--- " ---	--- " ---	--- " ---	--- " ---	1 - 25'	2 - 25' + ESF	--- " ---	--- " ---	5
15	32	C1	16' SHAFT	--- " ---	--- " ---	--- " ---	TWO LEVEL	--- " ---	NE	TWO LEVELS SAME AS REPOS.	2 - 25' ENLARGE ES - 1 25'	1 - 25' + ESF	--- " ---	--- " ---	4
16	33	C4	16' SHAFT	--- " ---	--- " ---	--- " ---	--- " ---	--- " ---	S	--- " ---	2 - 25'	--- " ---	--- " ---	--- " ---	5
17	34	R11	12' SHAFT	--- " ---	12' SHAFT	DRILL & BLAST	TITLE II G.A.	DRILL & BLAST	NE	SAME AS REPOS.	2 - 25'	2 - 25'	--- " ---	--- " ---	6

- Third, due to the uncertainties and the lack of data regarding the performance of options, the selection of an option necessarily involves judgment. Two types of judgments are involved -- (1) scientific judgments regarding what is likely to happen if a particular option is selected (i.e., judgments about what the consequences of an option might be) and (2) value judgments concerning preferences for different types of consequences (e.g., preferences for low radionuclide releases versus avoiding impacts on historical properties). Thus, the evaluation must provide means for obtaining accurate, unbiased judgments, while making the nature and sources of those judgments explicit.

- Fourth, DOE's selection of an option was expected to be controversial. Although the 34 candidate options collectively incorporated the various recommendations for design features that had been made, no single option can encompass all of the competing preferences that have been expressed. Thus, the rationale behind the final choice would likely be subjected to intense scrutiny. It was important, therefore, to select an evaluation methodology that would make the choice based on a highly defensible logic in a way that is open for review and relatively easy to understand.

1.5 Decision Analysis

In view of the above requirements, formal decision analysis was selected as the methodology for conducting the comparative evaluation. Decision analysis is a well-established mathematical approach that has been studied and practiced for over 25 years, with intellectual roots that go back several hundred years (Raiffa, 1968; Howard, 1968). Unlike most other decision methodologies, decision analysis is founded on a formal, prescriptive theory of decision making.

The ESF-AS evaluation methodology relied especially on three techniques used in decision analysis -- decision trees, Bayesian analysis, and multiattribute utility analysis (MUA). Decision trees provide a means for evaluating options under uncertainty (Bunn, 1984). Bayesian analysis provides a means for accounting for the effect of testing on uncertainty estimates (Thompson, 1982). MUA provides a means for evaluating decisions with multiple, possibly competing objectives (Keeney and Raiffa, 1976). For application to situations with limited data, decision analysis incorporates systematic procedures for obtaining and using expert judgments as a basis for assessing probabilities and preferences (Spetzler and Stael von Holstein, 1975; Keeney, 1977).

Decision analysis has been previously applied by DOE in the context of repository decision making. In 1986, DOE used MUA to rank five alternative sites for the repository (DOE, 1986; Merkhofer and Keeney, 1987). The DOE conducted this analysis after an earlier ranking process that identified three finalist sites was severely criticized by the National Research Council Board on Radioactive Waste Management (BRWM). Asked to review the report summarizing the application of MUA, the BRWM stated:

> *The Board commends DOE for the high quality of the chapters that were reviewed. The use of the multiattribute utility method is appropriate, and the Board is impressed by the care and attention to detail with which it has been implemented....*
>
> *... The multiattribute utility method is a useful approach for stating clearly and systematically the assumptions, judgments, preferences, and tradeoffs that must go into a siting decision. The Board strongly supports the DOE position that the methodology is best applied only as a decision-aiding tool and that additional factors and judgments are required to make final decisions about which sites to characterize.*

1.6 **Pilot Study**

A pilot study was conducted to test the feasibility of applying decision analysis to evaluate ESF-repository options. The pilot study consisted of a very rough, simplified application of decision trees, MUA, and methods for eliciting expert judgments to a few simplified options. The pilot study confirmed the applicability of these methods.

Although the pilot study was not intended to provide reliable numerical results, the analysis did suggest that certain considerations were important for judging the merits of alternative options. Specifically, the analysis suggested that the choice of an option might significantly affect the probabilities of future uncertain events and the ultimate consequences of a repository. For this reason, the methodology for the comparative evaluation was designed to include components capable of accounting for such considerations. These key components of the analysis are discussed in Section 2.

Although the pilot study confirmed the applicability of the decision analysis methods, it clearly demonstrated the critical importance of obtaining best-available expertise for the numerous judgmental inputs required for the analysis. Accordingly, care was taken to ensure participation of individuals with a wide range of technical expertise.

1.7 Participants and Process

The comparative analysis was conducted by a task force composed of approximately 80 people, including technical staff and management from the DOE, SNL, other DOE-YMP integrated contractors, support contractors, and consultants. Participants were organized into five major groups, as illustrated in Figure 1-3.

The first group, called the Sandia Management Lead Group, consisting of SNL managers and staff, was responsible for managing the overall study. The second group, called the Decision Methodology Group, consisted of decision analysts and technical specialists. The Decision Methodology Group was responsible for designing and applying the evaluation methodology. The third group, called the Design and Testing Support Group, consisted of designers, engineers, and testing experts responsible for developing the designs and supporting information for the 34 options. The Design and Testing Support Group was divided into three subgroups according to the different types of supporting information required -- a Design Support Group, a Cost Support Group, and a Characterization Testing Support Group.

The fourth and fifth groups consisted of various panels responsible for generating the two types of inputs required for the application of decision analysis: technical judgments and value judgments. Technical judgments involve questions of fact and logical inference, such as, "What is the probability that an event will occur?" Value judgments involve questions of preference, such as, "If the releases from a repository could be reduced slightly if the cost of the repository were doubled, would it be worth it?"

Technical judgments were provided by eleven panels of technical specialists, which formed the fourth group comprising the task force. Each panel was responsible for one or more of the following major technical areas:

- Aesthetics
- Biota
- Characterization Testing
- Cost and Schedule
- Historical Properties
- Postclosure Health

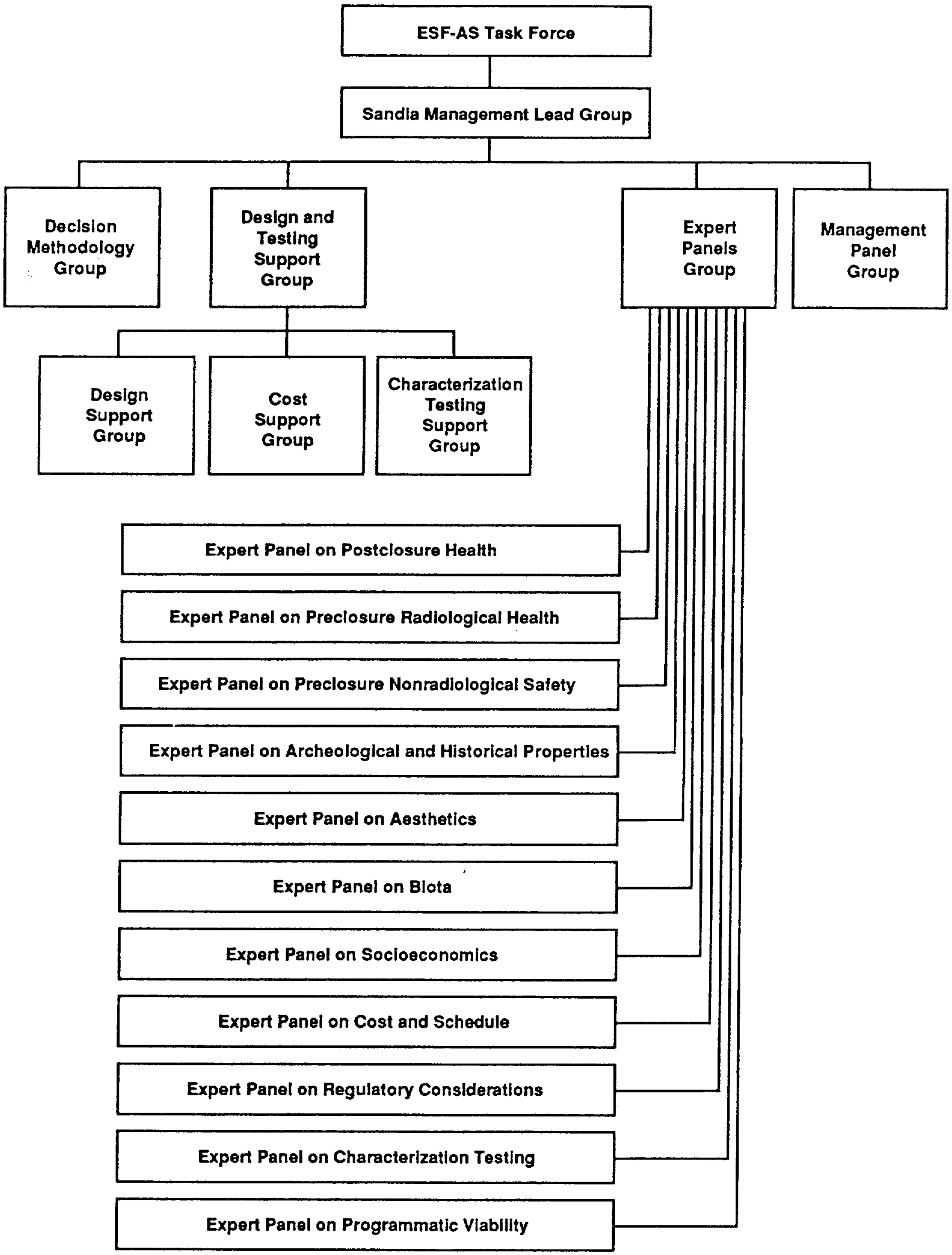

Figure 1-3. Chart Showing the Organization of the ESF-AS Task Force

- Preclosure Nonradiologic Safety
- Preclosure Radiologic Health
- Programmatic Viability
- Regulatory Considerations
- Socioeconomics.

The inputs to the analysis dealing with values were provided by the Management Panel, the fifth group composing the task force. The Management Panel consisted of senior managers familiar with the repository program. Appendix A describes the membership of the various groups and panels. The relevant qualifications of these individuals are also described therein.

The comparative evaluation, conducted primarily between January 1990, and December 1990, proceeded as follows. The Design and Testing Support Group provided the basic information needed by the various expert panels, including ESF-repository underground layouts, surface facility layouts, construction and testing schedules, materials usage, and cost estimates. In addition, members of the Testing Support Group provided evaluations of each of the 17 option pairs in terms of the impact of the configurations on the ability to conduct each of the planned characterization tests (see Appendices to Section 5 of Volume 1). With guidance from decision analysts, the expert panels developed the measures for quantifying the performance of each option; identified, developed, and analyzed scenarios for the development and operation of the ESF and repository; and provided estimates of the probabilities of uncertainties relating to the outcome of future events or scenarios. The Management Panel was responsible for specifying the objectives and criteria for the evaluation, the value tradeoffs among objectives, and the attitude toward risks used in the analysis.

Care was taken to maintain, to the extent possible, separation between technical and value judgments. The management panel was not informed of the technical assessments made by the technical panels prior to being asked to provide value judgments. Similarly, the technical panels were not informed about the value judgments made by the management panel prior to being asked to provide technical judgments.

1.8 Overview of the Remaining Sections of Volume 2

The remaining sections of this volume describe the comparative evaluation of the 34 candidate options. Section 2 explains the principal decision analysis techniques used in the evaluation: decision trees, Bayesian analysis, and MUA. Sections 3, 4, and 5 describe the methods used to obtain the necessary inputs: probability estimates, consequence estimates, and value estimates. Section 6 presents the nominal ranking results and a sensitivity analysis designed to determine the sensitivity of results to the various assumptions that were used. Section 7 summarizes the insights and conclusions from the comparative evaluation.

The appendices provide additional detail. Appendix A lists the study participants, their affiliations, and their roles in the study. Appendix B describes the process used to define and develop analysis inputs, including the graphic method, called influence diagrams, used to identify and structure the factors influencing the assessment of inputs. Appendix C presents additional details regarding the aggregation function used to combine the various inputs into an overall measure for ranking options. Appendix D outlines the records packages documenting the assessments derived from the expert panels.

2.0 KEY COMPONENTS OF THE ANALYSIS

This section of the report introduces the key components of the comparative evaluation: decision trees, Bayesian probability analysis, and multiattribute utility analysis. In addition, necessary technical background for understanding the analysis is introduced.

2.1 Critical Considerations

As indicated in Section 1, a pilot study that identified potential impacts of the selection of an ESF-repository option relevant to the achievement of program objectives was conducted. Initial discussions among the study task force were directed at clarifying these impacts. Obtaining a clear understanding of the impacts of the option choice was important because such impacts represent considerations that would have to be addressed by the comparative evaluation. The following four general types of impacts were identified.

- Impact 1: Programmatic Viability. Political support for the development of a repository at Yucca Mountain has always been tenuous, at best. Disappointment over limited progress and high costs threaten the viability of the program; therefore, termination of the program prior to the initiation of characterization testing is a possibility. Because the ESF-repository choice is viewed as a major and controversial decision, the option selected could increase or decrease the likelihood of the program being continued long enough to begin characterization testing.

- Impact 2: Characterization Testing. The choice of the ESF-repository option affects many aspects of the testing program, including the timing, location, and accuracy of the tests that are planned to assess the ability of the site to isolate waste. The ESF-repository option thus influences the ability of the characterization program to determine accurately whether or not the site is a suitable location for a repository.

- Impact 3: Regulatory Authorization. Thousands of regulatory requirements, including those established by Federal, State, and local laws, as well as comments and concerns of the NRC, NWTRB, and the State of Nevada, were viewed as potentially applicable to the design and construction of the ESF and to the associated repository design. Some of these requirements and concerns were identified as potentially discriminating; that is, in view of these requirements and the concerns, the choice of the ESF-repository option might affect the likelihood of obtaining the necessary regulatory authorization to construct and operate the repository.

- Impact 4: Closure of the Repository. The ESF and, especially, the repository determine the physical conditions at the site which, in turn, determine the ability of the program to achieve its fundamental objectives, such as minimizing adverse impacts to public health. Furthermore, because the decision to close the repository or retrieve emplaced waste will be delayed until the performance of the repository can be confirmed, the choice of the an option potentially influences the likelihood that emplaced waste might have to be retrieved.

The comparative evaluation would have to account for each of these types of impacts to be comprehensive and accurate. In other words, for each option, the method of analysis must estimate and account for (1) the likelihood of the program remaining viable, (2) the accuracy of the testing program, (3) the likelihood of obtaining necessary regulatory authorization, and (4) the likelihood that the repository would be closed and the ultimate consequences thereof.

To account for these considerations, the analysis involved three components -- (1) a decision tree model to represent the influence of the an option on subsequent uncertain events, (2) a Bayesian analysis to represent the influence of an option on testing, and (3) a multiattribute utility model to represent the influence of an option on ultimate consequences and the degree to which fundamental objectives will be achieved.

2.2 Decision Tree

Figure 2-1 shows the decision tree model used to represent the future events whose outcomes or probabilities might be influenced by the choice of an option as suggested by the four impacts outlined above. The decision tree provided a means for evaluating options using a defensible logic that accounts for these impacts. Major uncertain events

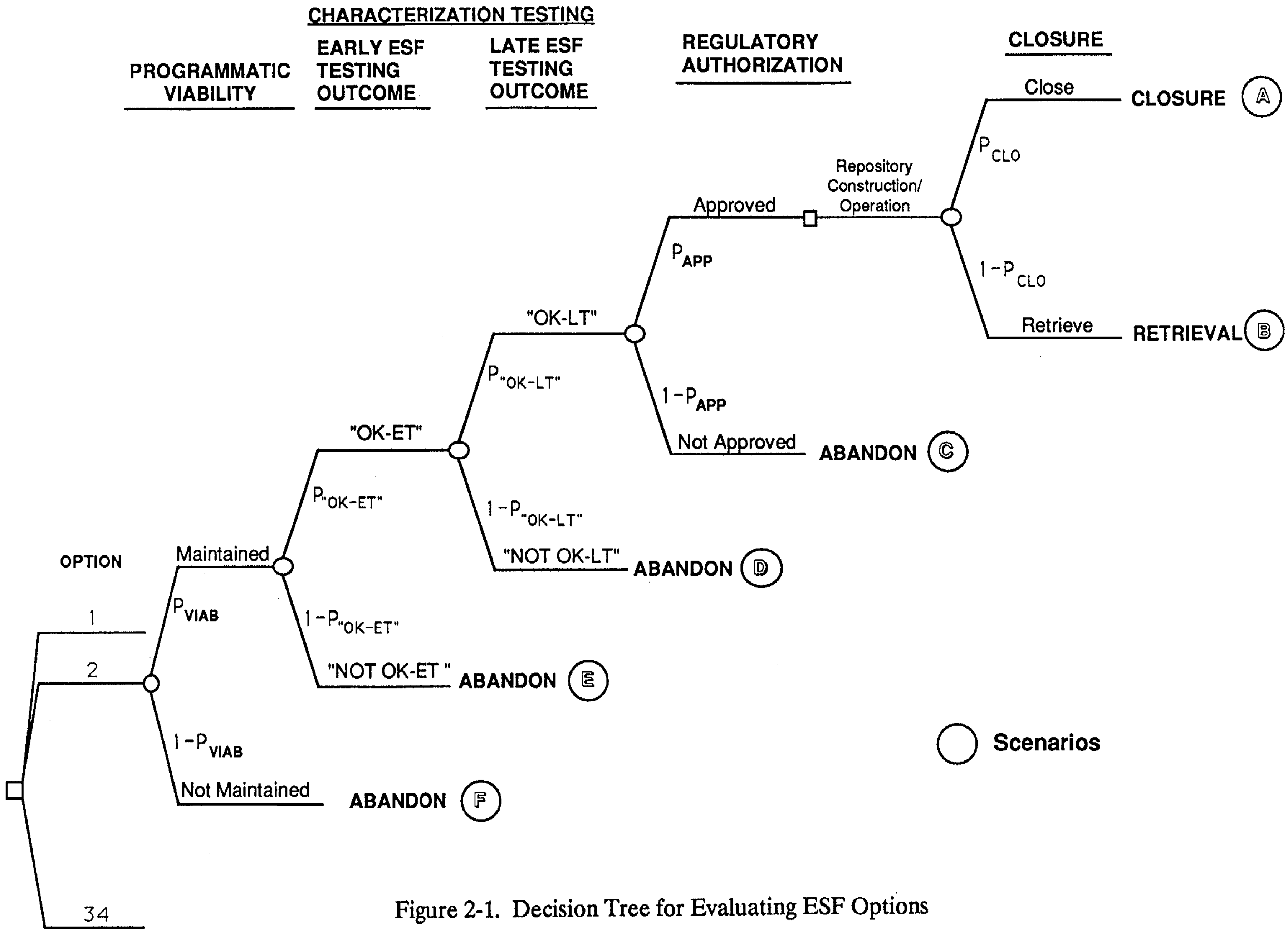

Figure 2-1. Decision Tree for Evaluating ESF Options

and DOE decisions are represented in the tree by nodes (circles for uncertainties, squares for decisions). The branches emanating from a node indicate the possible alternatives for decisions or outcomes for uncertain events.

Starting at the left of the tree, the selection of an option is the initial decision to be made. Once the option is selected, programmatic viability (Impact 1) is the first uncertainty to be resolved. If programmatic viability cannot be maintained, the site is assumed to be abandoned. If programmatic viability is maintained, characterization testing will be conducted.

Assuming the program continues until characterization testing, the impact of the ESF on testing is represented by the next two nodes in the tree (Impact 2). Testing is split into two distinct phases, early testing and late testing. This split was made in order to account for the potential advantage of options that allow for early tests relevant to assessing the site's ability to isolate waste -- if the site is quickly determined to be flawed, then the additional time and costs that would otherwise be wasted on the site will be saved. The specific tests that fall into the early or late phase depend on whether the option uses the original SCP testing strategy (Options 1 through 17) or the strategy emphasizing rapid progress to the CH unit (Options 18 through 34).

As illustrated in the decision tree, two possible outcomes to both early and late testing were defined: "OK" and "NOT OK." The outcome of testing was defined to be "OK" if the information obtained would cause the DOE technical community to conclude that there was sufficient confidence in the site to recommend that the next step be taken, i.e., a license to construct the repository should be sought. (A more precise definition of an "OK" result from testing is presented in the following section.)

If testing indicates that the site is "OK," the decision tree reflects an assumption that DOE would seek regulatory approvals to construct and operate the repository. As indicated by the node labeled regulatory authorization, these license applications are assumed to be either approved or not approved (Impact 3). If approval is obtained, the repository will be constructed and the waste will be emplaced. This decision is represented in the tree by the square node with the single branch. The final node, labeled closure, represents uncertainty over whether the repository ultimately will be closed, or alternatively, that the emplaced waste will be retrieved (Impact 4).

Note that the decision tree maps out six mutually exclusive scenarios for what might happen following the choice of an option, corresponding to the six paths through the tree labeled A through F. The consequences of each scenario differ significantly. For example, since only Scenario A results in a closed repository, releases following closure of the repository would occur only under Scenario A. Scenario B would result in retrieved waste at the site. Scenarios C through F would result in site abandonment occurring at various points in time, with waste not delivered to the repository.

The four impacts identified in Section 2.1 imply that the choice of the option affects both the consequences of each scenario and probabilities of the scenarios. For example, the releases that might occur from a closed repository in Scenario A would depend on the option chosen. The costs that would occur prior to site abandonment in Scenarios C through F would depend on the ESF portion of the option, because the option would determine the specific work that would be conducted. The choice of the option affects the probabilities of the scenarios by affecting the probabilities of the various events in the decision tree.

A decision tree, such as that in Figure 2-1, can be solved to obtain a "best" decision, provided that probabilities are assigned to each uncertainty node and consequences are estimated and valued for each path through the tree. Thus, much of the comparative evaluation consisted of estimating the probabilities of the events and the consequences of each scenario shown in the decision tree as a function of the option that is selected. (This work is described in Sections 3-5 of this volume.)

The option that is "best," according to decision analysis, is the choice that leads to the highest expected utility. Utility is a measure of value, and expected utility is the sum of the utility of the consequences associated with each path through the tree, weighted by the probability of that path. The option with the highest expected utility can be shown to be the option most preferred by decision makers, provided that the probabilities reflect the decision makers' uncertainties, the utilities assigned to consequences reflected the decision makers' preferences for those consequences and uncertainties, and the decision makers agree with several basic axioms of rationality. This result is called the "expected utility theorem" of decision analysis.[5]

Before the decision tree of Figure 2-1 could be used to evaluate, rank, and identify the best of the candidate options, probabilities had to be assigned to each uncertainty in the tree, and consequences estimated and valued for each path through the tree, as noted above. Before explaining the process by which this was accomplished, the remaining two components of the analysis are introduced.

2.3 Nature's Tree and Bayesian Analysis

In addition to the decision tree model outlined above, the analysis required another component to account for the influence of the ESF-repository option on the accuracy of testing. This was accomplished through a simple probability tree model, known as "Nature's Tree." The fundamental goal of testing is to determine whether or not the site is suitable for development as a repository. Although a judgment of suitability involves many considerations, the factor most likely to determine whether or not DOE seeks a license to construct and operate a repository was assumed to be whether or not DOE concludes that the repository at the site would meet an Environmental Protection Agency (EPA) standard for the release of radionuclides. The EPA standard requires that cumulative releases to the accessible environment shall

1. Have a likelihood of less than 1 chance in 10 of exceeding applicable EPA release limits, and

2. Have a likelihood of less than 1 chance in 1000 of exceeding 10 times the EPA release limits.

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[5] The fact that the expected utility theorem can be derived from basic axioms of rationality gives decision analyses its theoretical justification. That the axioms are readily accepted by most people may be illustrated by an example of one of the axioms, transitivity of preferences -- if the decision maker likes Option A better than Option B, and Option B better than Option C, than the decision maker must like Option A better than Option C. For a simple description of the six axioms underlying decision analysis, see Stokey and Zeckhauser (1978). A complete mathematical treatment is provided by Luce and Raiffa (1957).

The applicable EPA release limits are specified in Table 1 of Appendix A of 40 CFR Part 191 (EPA, 1987), in terms of the allowable cumulative releases of radionuclides to the accessible environment per 1000 metric tons of heavy metal (MTHM) for 10,000 years after repository closure.[6]

To represent uncertainty over the suitability of the site, based on the performance of the repository and future events, the following definitions were established.

> **OK** -- The site is defined to be OK if the site characteristics and conditions, including the ongoing processes, are such that, if the specified ESF-repository option were constructed, operated, and closed at the site, the resulting geologic repository system would meet the EPA radionuclide release limits for 10,000 years after closure.
>
> **NOT OK** -- Conversely, the site is defined to be NOT OK if the repository system would not meet the EPA radionuclide release limits.

With these definitions, the true state of the site (i.e., whether or not the site is OK) is an uncertainty. This true state will not be known unless and until the ESF-repository option is constructed and the repository is closed. The releases that would occur, over 10,000 years, would have to be measured, and the accumulated total compared with the EPA limit. If the total is less than the limit, the site is, by definition, OK.

As noted in the previous subsection and represented in the decision tree of Figure 2-1, the outcome of testing is an indication of whether the site is OK (denoted "OK") or NOT OK (denoted "NOT OK"). The quotation marks are used here to distinguish the outcome of the test (denoted by the quotes) from the reality (no quotes). The more precise definitions for the possible outcomes of testing are

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[6] Table 1 and Note 6 of Appendix A of the cited document indicate allowable cumulative releases of individual radionuclides for 10,000 years after repository closure. As explained by the EPA, a cumulative release of a mixture of radionuclides can be compared against the EPA standard by dividing the release quantity for each radionuclide in the mixture by the limit specified in the table and summing the results.

"OK" -- The outcome of testing is an indication that the site is OK (denoted "OK"), if the data obtained from the specified tests -- when analyzed using available methods and models and placed in the context of other previously available information -- are logically consistent with an opinion that the site would meet the EPA standard, that is, it would be estimated that there is less than 1 chance in 10 of exceeding the EPA release limits and less than 1 chance in 1000 of exceeding 10 times the limit. Under these conditions, the DOE technical community would consider that it is OK to proceed to the next step in the process.

"NOT OK" -- Conversely, the outcome of testing is "NOT OK" if the resulting information would lead the DOE technical community to conclude that the EPA standard would not be met.

The outcome of testing, according to these definitions, is determined by the probability distribution assigned to the site being OK, based on the results of characterization testing. Because the EPA standard has been expressed in terms of a constraint on this probability distribution, the possible outcomes of characterization testing were defined in an analogous way.[7]

Figure 2-2 shows the testing model. This probability tree was referred to in the study as "Nature's Tree", to distinguish it from the decision-maker's tree shown in Figure 2-1. Consistent with Figure 2-1, testing was split into two phases, early testing and late testing, with testing assumed to be terminated if the outcome of early testing is "NOT OK". Note that the probability tree includes the possibility of "OK" results from testing even if the site is in reality NOT OK. This result, known as a false positive outcome, could occur due to the inherent limitations of the science of testing and the impossibility of resolving all uncertainty about the site. Similarly, the tree allows for

[7] Normally, decision analysts avoid defining events whose outcomes fail to pass the "Clairvoyance Test" -- if an event is defined unambiguously, it should be possible for a clairvoyant (someone who could predict the future) to state unequivocally what the outcome of that event is. In this case, the clairvoyant would have to ask a question, "Whose probability distribution will be used to determine whether the constraint is met?" The answer to this question is not specified in the EPA standard. In addition to posing problems for the application of the standard (which, presumably, will be addressed when the NRC decides whether the standard has been met), this ambiguity increased the difficulty of assessing probabilities for the outcomes of testing. For the purposes of this study, participants were told to assume that the relevant comparison was between their personal probability distributions and the constraint on the distribution specified by the EPA standard.

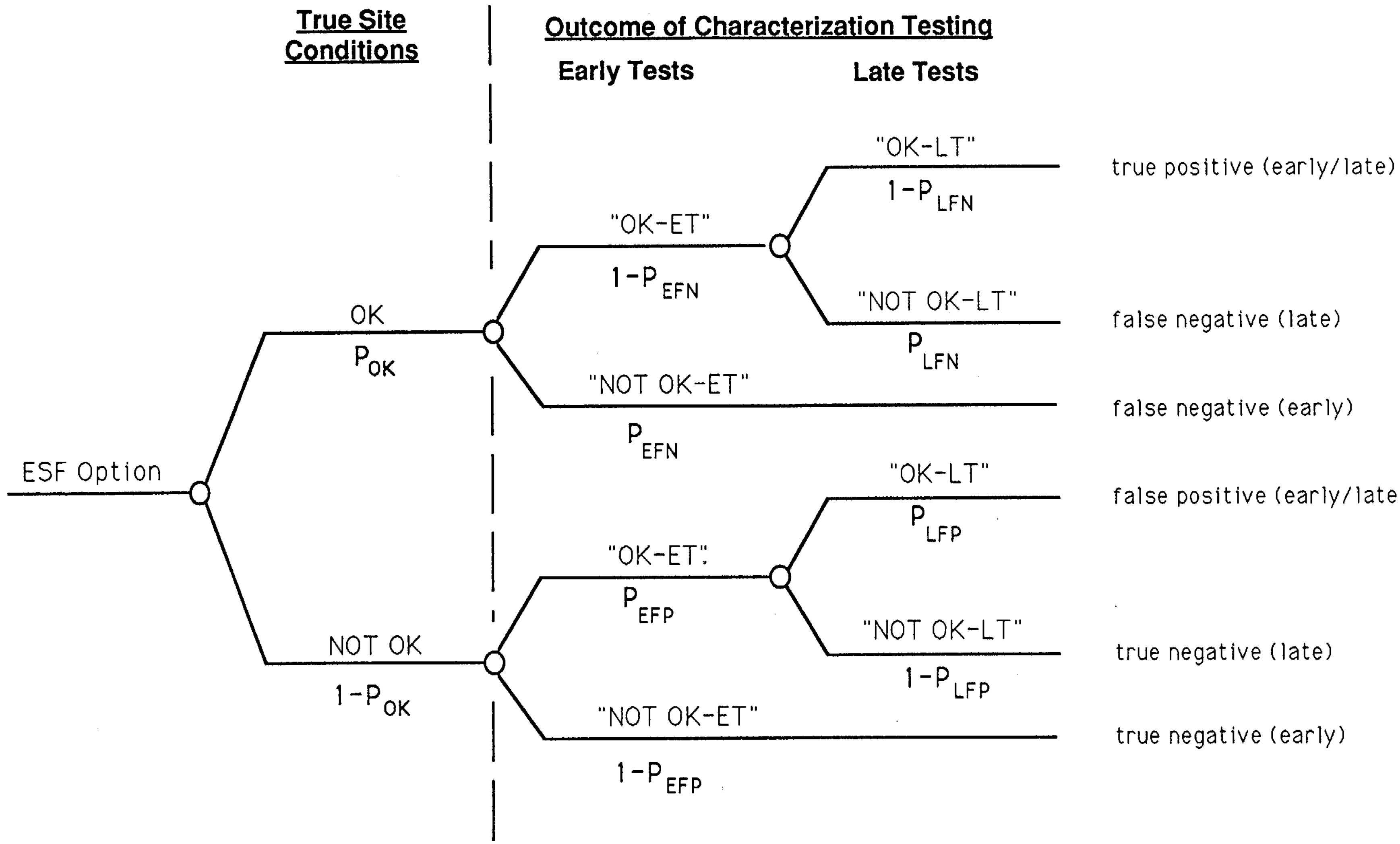

Figure 2-2. Nature's Tree

the possibility of a "NOT OK" result from testing even if the site is, in reality, OK. This possibility is known as a false negative outcome.

Like the decision tree of Figure 2-1, application of Nature's Tree requires probabilities for each branch in the tree. In this case, the required inputs are a "prior" probability that the site is OK (P_{OK}), and conditional probabilities for false positive and false negative outcomes of early and late testing (P_{EFP}, P_{LFP}, P_{EFN}, P_{LFN}). The probabilities of the various paths through Nature's Tree then give the probabilities of the possible outcomes of testing, which are needed for the decision tree.

Nature's Tree also provided a basis for applying Bayes' Theorem. Bayes' Theorem specifies how a prior probability distribution (based on an initial state of knowledge) should be updated to produce a "posterior" probability distribution that accounts for additional data. The prior probability, in this case, was the current estimated probability that the site is OK. The posterior probability was the probability that would be assigned after the results of testing become available.

Bayes' Theorem states the following. If P(H) is the prior probability that hypothesis H is true, P(D) is the probability that datum D will be observed, and P(D|H) is the conditional probability that D will be observed given that H is true, then the posterior probability that H is true given that D has been observed is[8]

$$P(H|D) = \frac{P(D|H)P(H)}{P(D|H)P(H) + P(D|\bar{H})P(\bar{H})} \qquad \text{(Eq. 2-1)}$$

Application of the theorem to the testing problem implies that the posterior probabilities that the site is OK, given the possible results of testing, are:

$$P(OK|\text{"}OK_{ET}\text{"}) = \frac{P_{OK}(1 - P_{EFN})}{P_{OK}(1 - P_{EFN}) + (1 - P_{OK})P_{EFP}} \qquad \text{(Eq. 2-2)}$$

$$P(OK|\text{"NOT }OK_{ET}\text{"}) = \frac{P_{OK} \bullet P_{EFN}}{P_{OK} \bullet P_{EFN} + (1 - P_{OK})(1 - P_{EFP})} \qquad \text{(Eq. 2-3)}$$

8 In this equation and in some subsequent notation, a bar over a letter or letters is used to indicate the complement outcome. Thus, for example, NOT H is denoted by a bar over the letter H. Similarly, NOT OK and "NOT OK" are denoted by a bar over OK or "OK", respectively.

$$P(OK|"OK_{ET}","OK_{LT}") = \frac{P_{OK}(1 - P_{EFN})(1 - P_{LFN})}{P_{OK}(1 - P_{EFN})(1 - P_{LFN}) + (1 - P_{OK})P_{EFP} \bullet P_{LFP}} \qquad \text{(Eq. 2-4)}$$

$$P(OK|"OK_{ET}","NOT\ OK_{LT}") = \frac{P_{OK}(1 - P_{EFN})P_{LFN}}{P_{OK}(1 - P_{EFN})P_{LFN} + (1 - P_{OK})P_{EFP}(1 - P_{LFP})} \qquad \text{(Eq. 2-5)}$$

The probabilities of the various paths through Nature's Tree are the probabilities of the possible outcomes of testing. These probabilities, which may be calculated from the following equations, are needed for the decision tree:

$$P("OK_{ET}") = P_{OK}(1 - P_{EFN}) + (1 - P_{OK})\,P_{EFP} \qquad \text{(Eq. 2-6)}$$

$$P("OK_{LT}"|"OK_{ET}") = \frac{P_{OK}(1 - P_{EFN})(1 - P_{LFN}) + (1 - P_{OK})\,P_{EFP}\,P_{LFP}}{P_{OK}(1 - P_{EFN}) + (1 - P_{OK})\,P_{EFP}} \qquad \text{(Eq. 2-7)}$$

The methods by which the probabilities for Nature's Tree were estimated, and the calculations, will be explained after the third major component of the evaluation, MUA, is introduced in the next subsection.

2.4 Multiattribute Utility Analysis

As explained in Section 2.2, application of the decision tree to evaluate options required the end consequences of each scenario in the tree to be estimated and valued. To model and value consequences, MUA was used (Keeney and Raiffa, 1976).

There are many different types of consequences that are potentially important to the evaluation of ESF-repository options, for example, the costs of the option, the level of health and safety that might be achieved, the impact on the natural environment, and so forth. Thus, multiple measures must be defined to account for the various types of consequences that are relevant. According to MUA, the appropriate measures for estimating consequences can be identified and then valued though a three-step process.

1. Identify decision objectives.

2. Establish performance measures for quantifying the degree to which objectives are achieved.

3. Develop a multiattribute utility function for valuing and aggregating the performance measures.

MUA was used in the analysis solely to model and value consequences in the decision tree. However, it was instructive to apply the MUA three-step procedure to the ESF selection problem. As shown in the following discussion, the procedure not only provided the measures needed for the decision tree, the results also tended to confirm the need for the decision-tree approach.

2.4.1 ESF Decision Objectives

The basic idea underlying MUA is that options should be valued in terms of the degree to which they achieve decision objectives. Thus, identifying and structuring objectives is the first step in MUA. The Management Panel was responsible for specifying ESF decision objectives.

The objectives of ESF-repository decision-making relate to the basic objectives of the repository program. The repository program recognizes that developing a repository will produce social costs as well as a potential social benefit. The potential social benefit is a solution to the problem of what to do with the high-level radioactive waste produced by nuclear power plants, waste that is currently being stored "temporarily" in storage pools at the reactor sites. Social costs include both economic costs and non-economic costs, such as adverse impacts to people and the natural environment.

As demonstrated by the decision tree, social costs and benefits depend differently on whether or not the repository will be closed. If the site is abandoned, there will be no closed repository, so the social benefit would be lost. On the other hand, abandoning the site would not eliminate the costs and adverse impacts that occurred prior to the decision to abandon. Thus, unlike benefit, adverse impacts are likely to occur whether or not the repository will be closed.

According to the Management Panel, repository decisions should be made with the objectives of maximizing benefit while minimizing adverse impacts.[9] Figure 2-3 displays

[9] The words "maximize" and "minimize" are used in objective hierarchies to indicate the direction of preferences, not to indicate that any one objective would be maximized or minimized without regard to other objectives. Typically, tradeoffs among objectives are necessary.

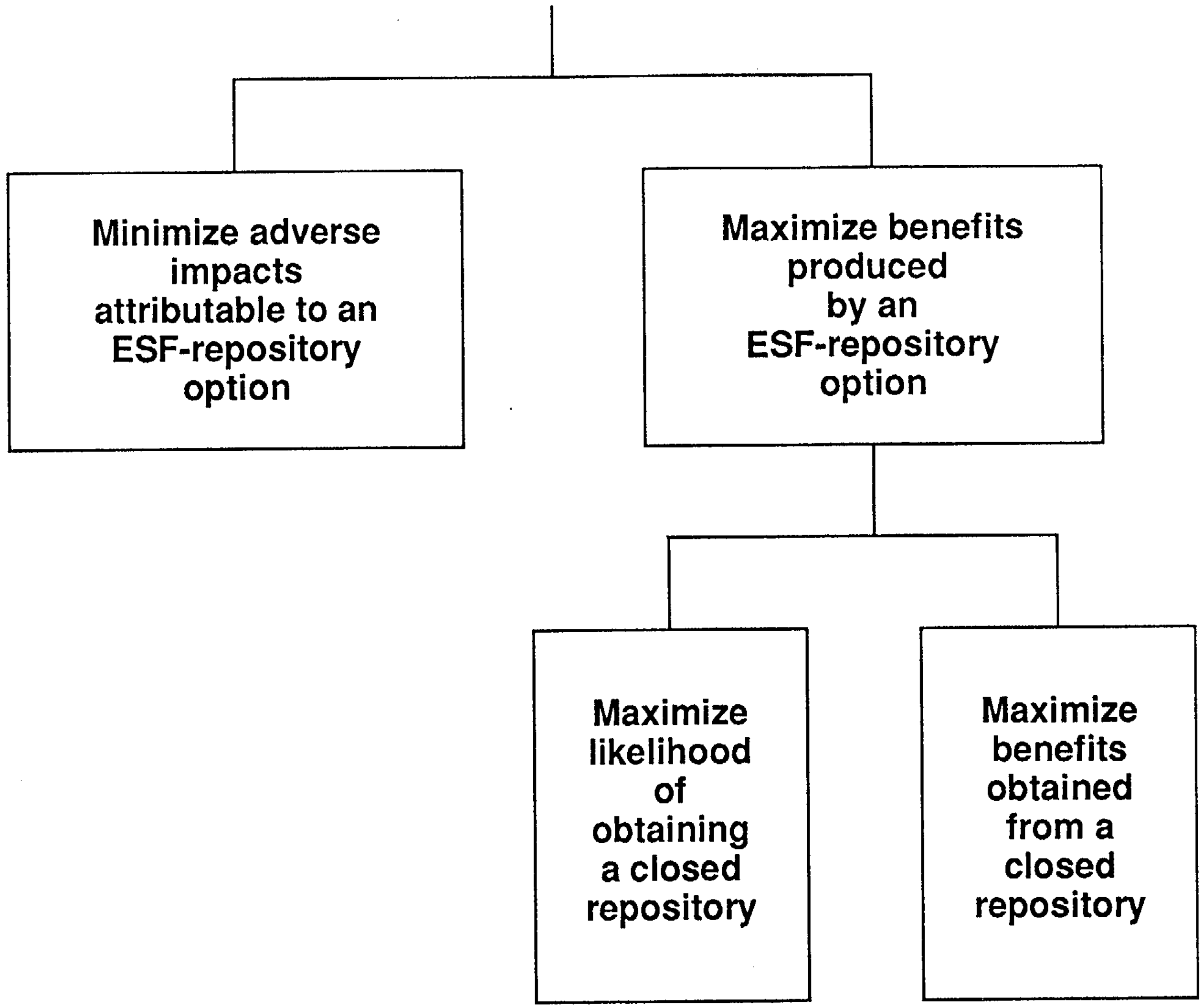

Figure 2-3. High-Level Objectives for ESF Decision Making

these high-level objectives in the form of a hierarchy. The objectives hierarchy makes the objective of maximizing benefit more specific in terms of the two lower-level objectives that specify how the benefits of a closed repository may be achieved. Benefit would be maximized if (1) the likelihood of obtaining a closed repository is maximized, for example, by ensuring that all necessary regulatory requirements are met, and (2) the benefits produced by a closed repository are maximized. All options were designed to the same functional requirements, so they do not differ in terms of the amount of waste that could be held, or other factors significantly affecting benefits to be achieved if the repository is closed. The options do differ, however, in terms of the likelihood of obtaining a closed repository, as reflected in the decision tree.

Objectives such as maximize likelihood of obtaining a closed repository and minimize adverse impacts are too general and high-level for direct use in MUA. Thus, these objectives had to be related to more specific, detailed objectives to permit the analysis to be conducted.

The MUA (DOE, 1986) of alternative repository sites referenced in Section 1 identified the detailed lower-level objectives for minimizing adverse impacts in terms of specific types of adverse impacts that should be minimized. These same types of impacts were determined by the Management Panel to be applicable to the ESF decision. Accordingly, the Management Panel adopted the various objectives used in the 1986 MUA with only minor revisions. Figure 2-4 shows the objectives related to minimizing adverse impacts organized into a hierarchy.

As illustrated in Figure 2-4, adverse impacts were divided into impacts that would occur during two mutually exclusive time periods -- preclosure and postclosure. The preclosure period is the time up to the point at which the repository is closed and involves impacts from construction of the ESF; testing; and construction, operation, and closure of the repository. The postclosure period is the time following repository closure.

Preclosure impacts were divided into impacts on health and safety, environmental impacts, socioeconomic impacts, and costs. Radiological health impacts and nonradiological health impacts were considered separately, as were potential impacts to ESF-repository workers and the public. The impacts to the environment of primary concern were impacts to the aesthetic qualities, including visual impacts associated with construction and operation; damage or disruption to historical properties; and adverse

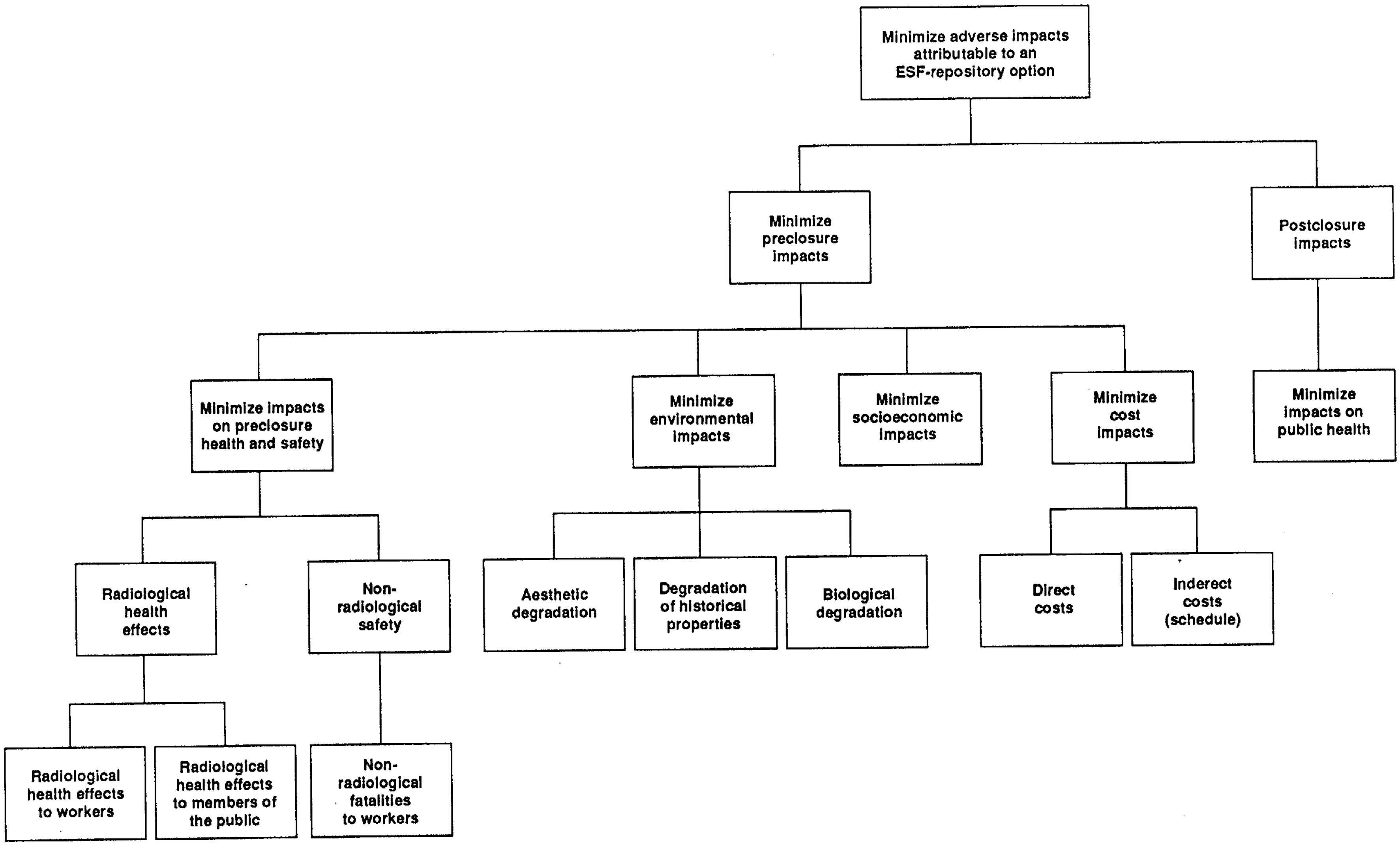

Figure 2-4. Objectives Hierarchy for Adverse Consequences

effects on plants and animals. Costs were divided into direct and indirect costs. Indirect costs reflected fixed overhead costs and account for the relative advantage of options that avoid delay.

During postclosure, the primary objective is the protection of public health. This concern is the motivation for the EPA regulation, described earlier, that specifies limits on radionuclide releases to the accessible environment during the first 10,000 years after repository closure. To reflect the time period established in the EPA regulations, the postclosure objective was defined as minimization of adverse health effects attributable to the repository during the first 10,000 years following closure.

In addition to the overall objective of minimizing adverse impacts, the high-level objective of maximizing the likelihood of achieving a closed, functioning repository must be considered when choosing an ESF-repository option. Indeed, were it not for this additional objective, the strategy for picking an option would be very different. Adverse impacts from an option could be minimized by picking an option that would guarantee that the ESF and associated repository would not be built!

Figure 2-5 shows that the objective of maximizing the likelihood of obtaining a closed repository is related to subobjectives specifying the events that must occur for the repository to be successfully closed -- programmatic viability, "OK" results from testing, regulatory approval, and closure. These are the same events as those shown in the decision tree (Figure 2-1).

As noted earlier, attempts to maximize achievement of any one objective in an objectives hierarchy would typically create problems for the achievement of others. Thus, tradeoffs are necessary. An important example of this is the objective "maximize likelihood of 'OK' results from testing." This objective could be pursued, for example, by performing only tests that cannot lead to negative outcomes. Although this would guarantee "OK" results from testing, it would likely preclude achievement of other important objectives, including programmatic viability, regulatory compliance, and achieving a closed functioning repository that minimizes adverse impacts. Thus, as demonstrated in Section 3, the most desirable testing strategies are those that most accurately determine whether the site, with the specified repository is, in reality, OK or not OK.

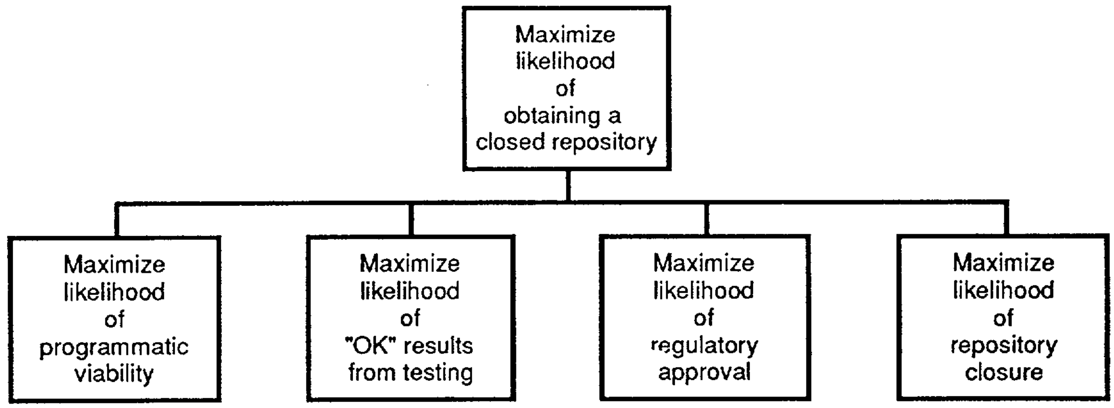

Figure 2-5. Objectives Hierarchy for Obtaining a Closed Repository

The objectives hierarchies shown in Figures 2-3, 2-4, and 2-5 collectively identify the major objectives identified for the option choice. The next step in the MUA process was to find a means for measuring the degree to which objectives are achieved. This was accomplished by defining a performance measure for each lowest-level objective in the objectives hierarchies.

2.4.2 Performance Measures

Performance measures were developed in a series of meetings between the Decision Methodology Group and the expert panels responsible for the relevant subject areas. In the development of the performance measures for this study, the expert panels elected to use the relevant performance measures from the earlier MUA of repository sites.

Appendix B contains a detailed description of the performance measures developed for the evaluation. Table 2-1 summarizes the measures defined for the lowest-level objectives in Figure 2-4, i.e., the objectives related to minimizing adverse impacts. As shown, direct, natural scales were used for performance measures when possible. Numbers of fatalities were selected as performance measures for quantifying nonradiological health objectives, and expenditures (expressed in millions of discounted dollars) were selected as the performance measure for costs. Pre-closure radiological health was quantified in terms of exposures to radioactivity, expressed in person-rems. Those objectives for which direct natural measures were unavailable require detailed discussion, presented below.

TABLE 2-1

OBJECTIVES AND PERFORMANCE MEASURES FOR ADVERSE CONSEQUENCES

Objective	Performance Measure	Symbol	Units
Minimize impacts on post-closure public health	Postclosure releases	X_1	fraction of limit specified by EPA standard
Minimize radiological health effects to workers	Radiological exposures to workers	X_2	person-rems
Minimize radiological health effects to the public	Radiological exposures to the public	X_3	person-rems
Minimize nonradiological effects to workers	Worker nonradiological fatalities	X_4	fatalities
Minimize aesthetic impacts on the environment	Constructed scale for aesthetic impacts	X_5	0, 1,2,3,...,12
Minimize degradation of historical properties	Weighted areal extent of mitigated property sites	X_6	hectares
Minimize ESF-repository direct costs	Direct costs	X_7	millions of discounted dollars
Minimize ESF-repository indirect costs	Indireet costs	X_8	millions of discounted dollars

As in the previous MUA of repository sites, a surrogate measure was adopted for quantifying postclosure health, namely, the cumulative radionuclide releases to the accessible environment expressed as a fraction of the limit allowed by the applicable EPA standard.[10] The reason for not using a direct measure for postclosure health, such as person-rems exposure or numbers of cancer fatalities during the first 10,000 years after closure, is the difficulty of predicting such numbers, given their dependence on the size, distribution, and needs of future populations.

Because no direct measure currently exists for quantifying adverse impacts on historical properties, a surrogate measure was also used for this environmental impact objective. The issue with respect to historical properties is as follows. The land around the Yucca Mountain site is undeveloped, and there are numerous undisturbed properties of historical value in the vicinity, such as Native American artifacts and campsites. The locations of many such properties are known and some fall within the area affected by the ESF-repository options. To the extent possible, these properties will be avoided. However, those historical properties that cannot be avoided will be mitigated. Mitigation, in this context, means excavating and recovering the available research data from the site. This sort of mitigation, however, is not 100 percent effective. Some information and/or some context value would inevitably be lost.

To develop an appropriate surrogate measure of the losses from mitigating unavoided historical-property sites, the Expert Panel on Archaeological and Historical Properties used a process involving the construction of an influence diagram (Merkhofer, 1990). (Influence diagrams will be discussed in Section 3.) Key factors influencing mitigation losses were determined to be the areal extent and whether a site is above or below the ground surface. More specifically, the panelists estimated that the potential for data

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10 As noted previously, Table 1 in Appendix A of 40 CFR Part 191 specifies, in terms of curies per 1000 MTHM, the allowable cumulative releases of individual radionuclides for 10,000 years after repository closure. As explained by Note 6 in Appendix A of 40 CFR Part 191, a cumulative release of mixture of radionuclides can be compared against the EPA limits by dividing the release quantity for each radionuclide in the mixture by the limit specified in the table and summing the result. The repository was assumed to contain 70,000 MTHM. Thus, the estimated releases from a repository at a given site can be expressed as a fraction of multiple of the same weighted total allowed by the EPA limits. The statement "the releases estimated for the repository during the first 10,000 years are equal to 0.1 of the EPA limits" means that the weighted sum of the cumulative releases of various radionuclides over this period is estimated to be one-tenth of the EPA limit.

loss would be directly proportional to areal extent and five times greater for subsurface sites than for surface sites. Accordingly, the performance measure for degradation of historical properties, X_6, was defined as the weighted areal extent (in hectares) of sites within the area of the ESF-repository option.

$$X_6 = \sum_{i=1}^{N} S_i \, x \, F_i \, , \qquad \text{(Eq. 2-8)}$$

where N is the number of historical-property sites within the area that would not be in the area common to all options,[11] S_i being the areal extent of site i, and F_i being equal to 1 if the *i*th site is surface and 5 if it is subsurface.

In the case of aesthetic impacts, no obvious direct or indirect performance measures were available. Consequently, a performance measure scale for this objective was constructed. A constructed scale consists of descriptions of distinct levels of impact.

Table 2-2 shows the scale constructed to quantify aesthetic impacts by the Expert Panel on Aesthetics. The major impact of concern is the degree to which ESF and repository activities degrade the scenic quality of the area. The scale was developed, as above, through a process involving the construction of an influence diagram. The process identified two considerations as being important determinants of the degree of scenic degradation: (1) the magnitude of the scenic impact, and (2) the visibility of the impact to populations.

As described in Table 2-2, scenic impacts were termed minor, moderate, or major depending on how noticeable or potentially offensive they are. For example, roadcuts and traffic were considered minor impacts while skyline structures, such as headframes and microwave towers, were considered major impacts. The visibility of impacts to people was determined by the number of vantage points from which such impacts would be visible. Vantage points are locations, such as roads, rest stops, and local communities, where people could see the impacts. Sketches illustrating the surface

[11] Historical sites contained in the area common to all options (such as the area for the waste-handling facility) were not considered because they would not provide any basis for discrimination among the options.

TABLE 2-2

CONSTRUCTED PERFORMANCE-MEASURE SCALE FOR AESTHETIC IMPACTS

Impact Level	Description
12 (Best)	No impacts visible from any vantage point
11	Minor impacts (roadcuts/traffic) visible from one vantage point
10	Minor impacts (roadcuts/traffic) visible from multiple vantage points
9	Moderate impacts (structures/facilities) visible from one vantage point
8	Moderate impacts (structures/facilities) visible from one vantage point plus minor impacts (roadcuts/traffic) visible from one vantage point
7	Moderate impacts (structures/facilities) visible from one vantage point plus minor impacts (roadcuts/traffic) visible from multiple vantage points
6	Moderate impacts (structures/facilities) visible from multiple vantage points
5	Moderate impacts (structures/facilities) and minor impacts (roadcuts/traffic) visible from multiple vantage points
4	Major impacts (skyline structures) visible from one vantage point
3	Major impacts (skyline structures) visible from one vantage point plus minor impacts (roadcuts/traffic) visible from multiple vantage points
2	Major impacts (skyline structures) visible from one vantage point plus moderate impacts (structures/facilities) visible from multiple vantage points
1	Major impacts (skyline structures) visible from multiple vantage points
0 (Worst)	Major impacts (skyline structures), moderate impacts (structures/facilities), and minor impacts (roadcuts/traffic) visible from multiple vantage points

appearance for the various options, provided by the designers, established a means for scoring options using the constructed scale.

In two cases, socioeconomic impacts and biological degradation, no performance measures were defined. For biological degradation, the objective was judged to be nondiscriminating given the available level of design and site information and understanding. During the process of defining performance measures, the members of the Expert Panel on Biota determined that they could identify no basis for concluding that any given option was likely to produce more or less impacts on plants and animals than any other option. For socioeconomic impacts, the expert panel believed that the level of detail in the information available regarding employment, purchases, and other related socioeconomic impacts for each option was not sufficient to make a determination concerning socioeconomic factors. Although some differences in socioeconomic impacts of the various options may exist, the panelists concluded that there was no means available to measure these differences.

In addition to the performance measures for quantifying adverse consequences (Table 2-1), the MUA concept of performance measures can also be applied to the other ESF decision objectives identified in Figures 2-3 and 2-5. Table 2-3 lists the performance measures defined for the lowest-level objectives shown in the objectives hierarchy of Figure 2-5. Probabilities provide the natural language for quantifying likelihood.

One additional performance measure was needed to ensure that a measure would be defined for each lowest-level objective in the objectives hierarchies. A measure was needed for the last objective shown in Figure 2-3, "maximize benefit obtained from a closed repository." This high-level objective was not made more specific because, as explained previously, the benefit was not expected to vary from option to option. For completeness, however, a measure of benefit, denoted B and expressed in equivalent dollars, was defined to quantify the benefit obtained from a closed repository.

2.4.3 Multiattribute Utility Function

Aggregating the various performance measures to obtain an overall measure of the desirability of each option required constructing a multiattribute utility function. The multiattribute utility function is an equation that combines the various performance measures in a way that accounts for value tradeoffs and attitudes toward risk. A critical step in MUA is determining the appropriate functional form for the utility function.

TABLE 2-3

OBJECTIVES AND PERFORMANCE MEASURES FOR OBTAINING A CLOSED REPOSITORY

Objective	Performance Measure
Maximize likelihood of programmatic viability	Probability of programmatic viability
Maximize likelihood of "OK" results from testing	Probability of "OK" results from early testing; Probability of "OK" results from late testing
Maximize likelihood of regulatory approval	Probability of regulatory approval
Maximize likelihood of repository closure	Probability of closure

Additive Utility Functions -- An additive equation is the simplest form used in applications of MUA. This form may be written:

$$U(X_1,...,X_n) = \sum_{i=1}^{n} w_i \bullet U_i(X_i) \qquad \text{(Eq. 2-9)}$$

where U is multiattribute utility, X_i, i = 1, ..., n, are performance measures, U_i are single-attribute utility functions, and w_i are scaling factors (i.e., weights). With the additive form, the aggregation equation consists of (1) transforming each measure to a common unit while accounting for any nonlinearities in the importance of achieving various levels of performance, (2) weighting each measure according to its relative importance as determined by value tradeoffs, and (3) summing the results.

The additive utility function in Equation 2-7 is the form used in almost all practical applications of MUA. The reason for this is that there are few functional forms other than additive that permit weights and single-attribute utility functions to be obtained relatively easily. The additive form is appropriate, provided that the performance measures satisfy certain independence requirements. For rigorous applications of MUA, it is essential that the independence requirements justifying an additive form be verified. Such verification was obtained in this study, as discussed in Section 5. Applications that adopt the additive form for performance measures that fail the independence checks are not logically defensible and often produce results that are in error (Rowe et al., 1981; Hobbs, 1982).

Fundamental versus Means Objectives -- To help ensure selection of an appropriate form for the multiattribute utility function, it is useful to distinguish between two types of objectives: fundamental objectives and means objectives. Fundamental objectives specify the essential reason for interest in the decision problem. Health, safety, and environmental protection, for example, are all fundamental objectives. The objectives hierarchy of Figure 2-4 consists entirely of fundamental objectives.

Means objectives are important because their achievement permits fundamental objectives to be met. The objectives hierarchy of Figure 2-5 consists entirely of means objectives. For example, the objective of obtaining a functioning repository is a means objective -- it is important only to the extent that it provides a means for safely disposing of nuclear waste. The objectives hierarchy of Figure 2-3 contains the objectives hierarchies of Figures 2-4 and 2-5 as subobjectives. Thus, the objectives hierarchy of Figure 2-3 contains both fundamental and means objectives.

Independence Tests -- A reason for distinguishing between fundamental and means objectives is that means objectives often fail to satisfy the critical independence tests that justify an additive form for the utility function. Roughly speaking, two objectives are said to be additive independent if the importance of achieving any one objective does not depend on the extent to which the other objective is achieved. (A more precise definition is given in Section 5.) Objectives such as health and the environment are generally assumed to be additive independent -- the importance of protecting public health, for example, neither diminishes nor becomes more important depending on the level of degradation that occurs to natural environment. Objectives like programmatic viability and regulatory approval, however, are not additive independent -- maintaining programmatic viability diminishes in importance if the probability of regulatory approval is reduced to a very small level.

Additive Utility Function -- The implication of the above result is that, although a weight-scale-and-add technique could be used with the performance measures shown in

Table 2-1, this approach could not be used for performance measures related to programmatic viability, characterization testing, regulatory approval, or closure of a repository (see Section 5 for a more rigorous verification of this result).

Fortunately, the decision-tree approach described in Section 2.2 requires only the provision and valuation of measures for end consequences. Because only fundamental objectives relate to end consequences, the performance measures in Table 2-1, plus the measure B for the benefit of a closed repository, provide the consequence measures needed for the decision tree. A simple additive multiattribute utility equation could thus be used to value these measures.

The performance measures related to means objectives, Table 2-3, have already been represented in the decision tree. Since the decision tree specifies the logically correct way to account for these measures (a multiplicative equation, as determined by the expected utility theorem), the evaluation methodology correctly deals with both the fundamental and means objectives governing the selection of an option.

2.5 Data for the Evaluation

The above subsections described the basic components of the analysis -- a decision tree representing the possible future scenarios resulting from the option choice, Nature's Tree for computing the probabilities of test outcomes, performance measures describing the end consequences of each scenario in the decision tree, and a multiattribute utility function for valuing consequences. The analysis consisted of applying these components according to the following five steps:

1. Assessment of the five probabilities necessary to quantify Nature's Tree, and use of the tree to compute testing outcome probabilities and other probabilities important to judging testing accuracy as a function of the ESF-repository choice;

2. Assessment of the other three probabilities needed for the decision tree (probabilities of programmatic viability, regulatory approval, and closure);

3. Assessment of the eight consequence measures for each scenario in the decision tree;

4. Assessment of the scaling functions and weights for the multiattribute utility function; and

5. Solution of the decision tree to obtain an overall evaluation and ranking of the 34 options.

The remaining sections of this report describe these steps.

3.0 PROBABILITY ASSESSMENTS

3.1 Process

The decision-tree and Nature's Tree components of the evaluation methodology contain eight probabilities that had to be estimated for each of the 34 options. As noted previously, the probability estimates were obtained from expert panels using a formal, systematic process. For the purposes of the study, the process of generating probabilities (and consequence estimates -- see Section 4) was termed "scoring." This section describes the scoring process used to obtain probability estimates.

Figure 3-1 provides an overview of the process. First, for each probability estimate, an influence diagram was constructed to summarize and display the factors and features of an option that influence the probability to be estimated. The lowest-level (i.e., most detailed) factors in the diagram were then used to generate a set of comparative evaluation questions. Each panel member was asked to estimate how well each option would perform with respect to each factor, compared to how well Option 1 (the base case) was estimated to perform with respect to that factor. The various comparative evaluations were then aggregated, across factors and across panel members, to obtain a single, qualitative ranking of the options that accounts for all factors in the relevant influence diagram. The panel then discussed and modified this initial ranking based on the issues and considerations raised. This qualitative ranking was used to facilitate the last step in the process -- obtaining quantitative probability estimates for each option.

The various probability estimates had to be conducted in a specific order because the outputs of some panels served as inputs to other panels. This was the case if the influence diagram developed for a panel included, as an influencing factor, the probability estimate (or consequence estimate -- see Section 4) provided by another panel. For this reason, the probability estimates were developed in the following order.

First, the four probabilities in Nature's Tree that define testing accuracy, the probabilities of an early false positive, late false positive, early false negative, and late false negative, were estimated by the Expert Panel on Characterization Testing. Second, the prior probabilities that the site is OK were estimated by the Expert Panel

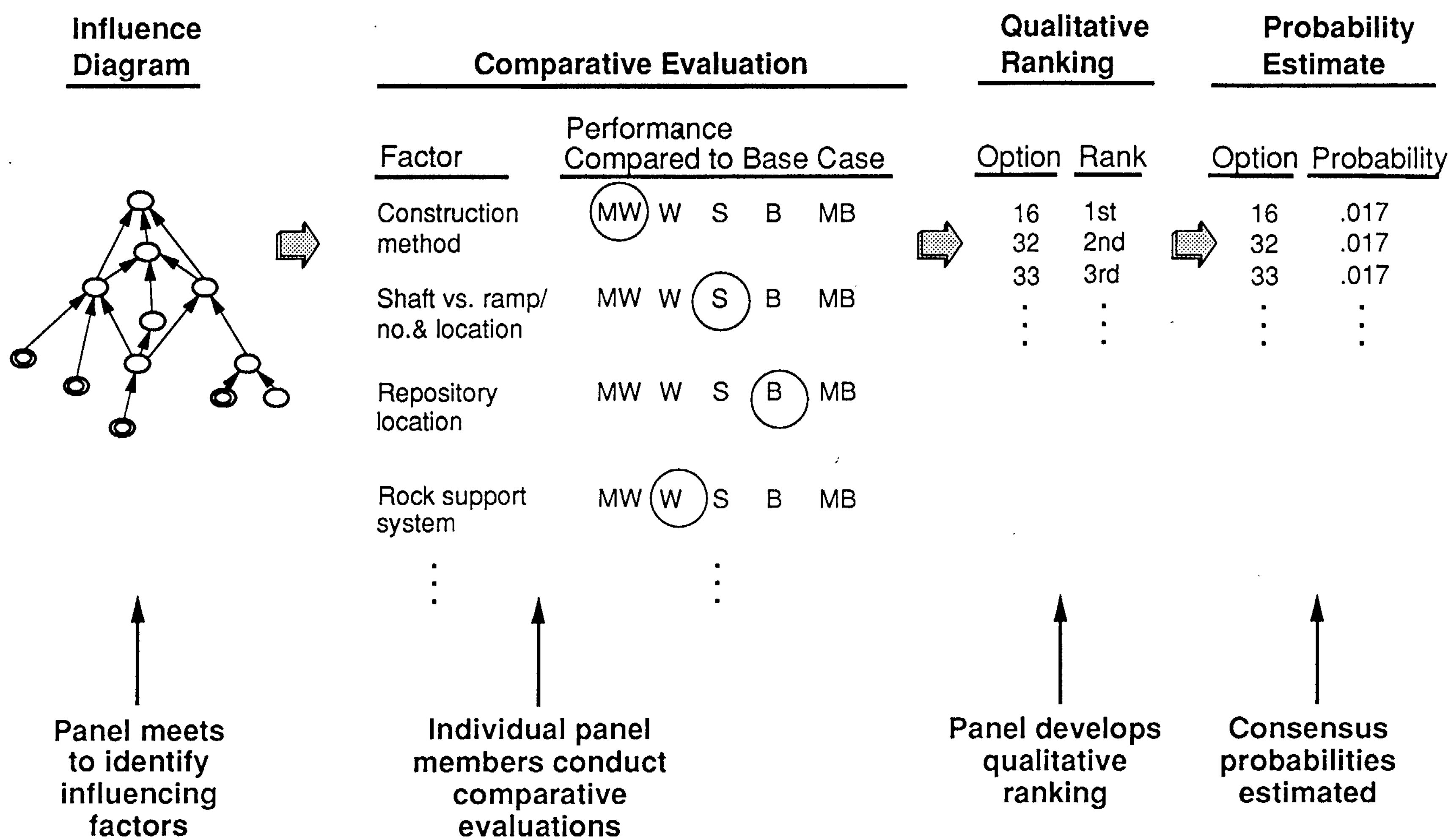

Figure 3-1. Overview of the Process for Generating Probability Estimates

on Postclosure Health. By application of Bayes' Theorem, Nature's Tree was then "solved" to obtain (1) the probabilities of "OK" results from early testing and from late testing (using Equations 2-6 and 2-7) required for inputs to the decision tree and (2) the residual probability that the site is NOT OK, given that the results from both early and late testing indicate that it is "OK" (using Equation 2-4), for use as a discriminating factor by the Expert Panels on Regulatory Considerations and Programmatic Viability. Next, for input to the decision tree, the probabilities of regulatory approval and repository closure were estimated by the Expert Panel on Regulatory Considerations. As the last step, the probability of near-term success in maintaining programmatic viability was estimated by the Expert Panel on Programmatic Viability.

Formal probability assessment methods were used throughout the scoring process to obtain consensus probabilities from panels. All of the scoring sessions, as well as those sessions in which the influence diagrams were developed, were facilitated by the Decision Methodology Group and formally recorded by a court reporter, with summary notes prepared by a member of the Decision Methodology Group (see Appendix B, B.1.1 through B.1.8; B.2.1 through B.2.8; and Appendix D, D.4, D.12, D.13, and D.15). In addition, technical support was provided during the sessions, as appropriate, by representatives of the Sandia Management Lead Group and the Design and Testing Support Group.

3.1.1 Influence Diagrams

As outlined above, the process of obtaining estimates of the probabilities for each of the 34 options (i.e., "scoring") was preceded by the development of an influence diagram for each of the eight probabilities. An influence diagram is a graphic representation of the relationships among factors that influence a performance measure, in this case a probability. As an example, Figure 3-2 shows the influence diagram that was developed to facilitate the assessment of the probability of programmatic viability.

This diagram was developed by members of the Expert Panel on Programmatic Viability during the course of several formal elicitation sessions. As noted previously, transcripts of these sessions were generated to document the process. (See Appendix D.) At the outset of a session, the panel members were asked to identify factors that, in

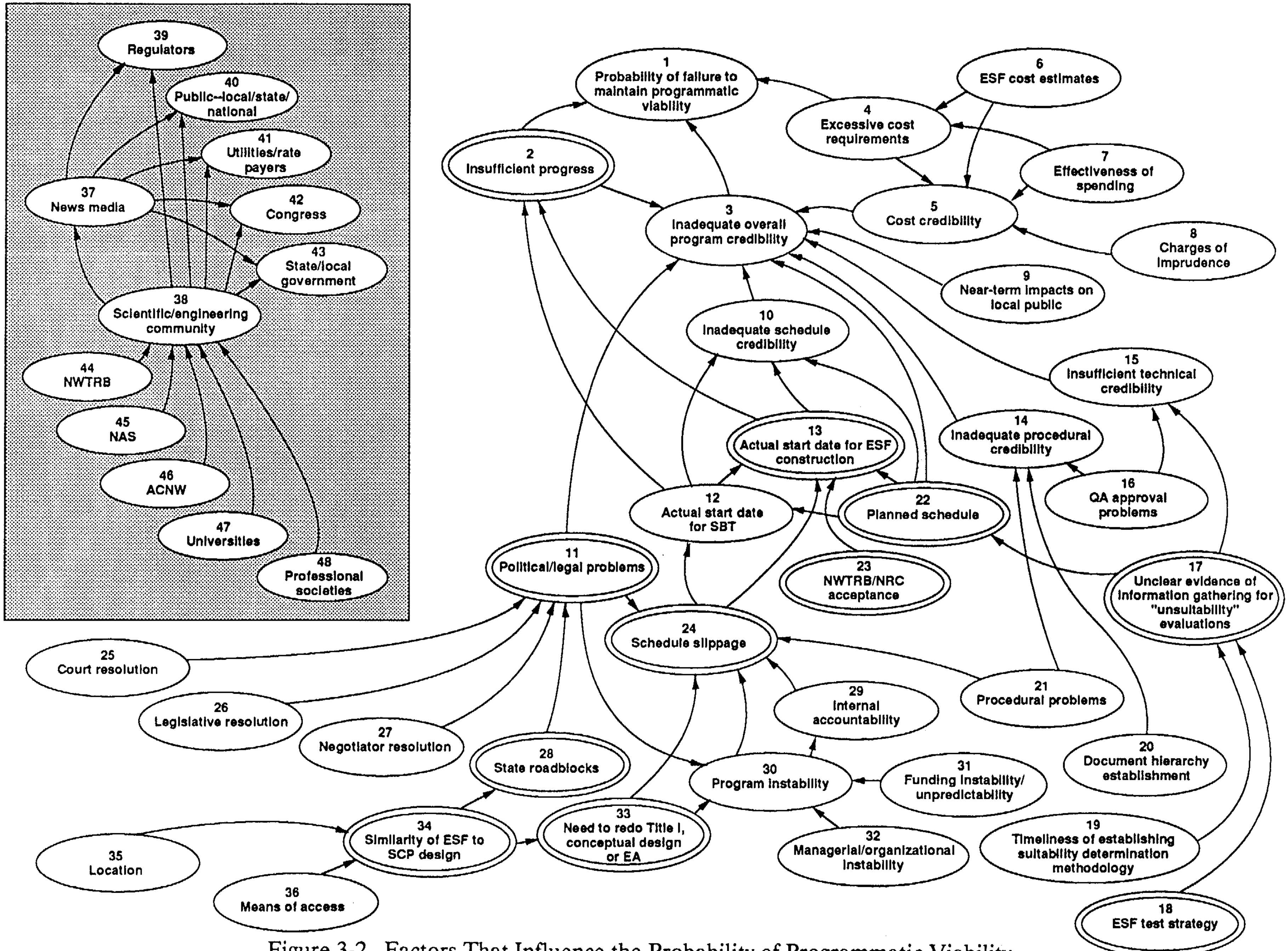

Figure 3-2. Factors That Influence the Probability of Programmatic Viability

their best judgment, would influence the likelihood of failing to maintain a viable repository program through the initiation of site characterization. Then, with the assistance of the session facilitators, the factors were organized into an assemblage that was logically ordered in terms of influence. The highest-level node , or "bubble," in the diagram of Figure 3-2 represents the probability of failure to maintain program viability, which is equal to one minus the probability of success in maintaining programmatic viability. The connected sequences of lower-level bubbles contain factors judged to influence the probability estimate. The factors contained in the lowest-level bubbles are identifiable aspects or features of the individual options. The factors contained within "double bubbles" were judged by the panelists to provide a significant basis for discriminating between and among options in terms of the likelihood of failing to maintain program viability.

Influence diagrams, such as that shown in Figure 3-2, are sometimes used as models for the indirect assessment of probabilities (Shachter, 1986). This requires assessing conditional probability distributions for all of the lower-level factors in the diagram. In this analysis, influence diagrams were not used as models for the indirect assessment of probabilities. Given the complexity of the influence diagrams that were developed, using influence diagrams to indirectly compute probabilities was not feasible.

Instead, influence diagrams were used as "knowledge maps" (Howard, 1990) to facilitate the direct assessment of the top-level probabilities in the diagrams. Use of influence diagrams in this way serves three useful purposes (Merkhofer, 1990). First, an influence diagram was developed for each probability to be assessed in order to provide documentation of the factors and logic used by expert panels when making the probability judgments. Second, the factors identified in the diagrams were used to develop comparison questions to be answered by panel members as part of the process used to prepare panel members for the probability encoding task (see following section entitled "Conditioning the Expert Panel for the Encoding Task"). Third, the influence diagrams were used to facilitate the encoding task itself by serving as a reminder to panel members of the considerations to be taken into account. The diagrams were referred to frequently in the assessment sessions and provided a framework for organizing debate over the probabilities and relative performance of the various options.

In addition to playing a role in the scoring process, influence diagrams such as Figure 3-2 provided a means for checking whether the comparative evaluation was comprehensive in its ability to account for requirements and concerns. As indicated in Section 1 and Figure 1-1, the ESF-AS included efforts to identify potentially discriminating requirements and concerns for the selection of an option. The identified requirements and concerns were cross-correlated to the factors contained in the influence diagrams. All such requirements and concerns were found to be captured by one or more influence diagram factors. The draft copy of the crosswalk between requirements and influence diagram factors was made available to the panels during the scoring process. This procedure helped ensure that the essence of each requirement (as expressed by specific bubbles in the influence diagram) would be considered by the relevant expert panel as it evaluated each option.

3.1.2 Stages of the Probability Encoding Process

The scoring process was patterned after the Stanford Research Institute (SRI) probability encoding process, which involves a sequence of formally structured stages (Stael von Holstein and Matheson, 1979; Merkhofer, 1987a). This process has many of the characteristics recommended by Bonano et al. (1990) in a report prepared for the NRC on the elicitation and use of expert judgment. For the ESF-AS, the process included (1) motivating the members of an expert panel; (2) structuring the uncertain variable to be assessed; (3) conditioning the panel members for the encoding task; (4) actually encoding and quantifying judgments; (5) resolving differences among the panel members and aggregating probabilities to form a possible basis for consensus; and (6) generating a set of consensus probabilities and verifying that the selected probabilities represent the panel's recommendation for use in the comparative evaluation of the 34 options. To illustrate the scoring process, the sequence of steps used to encode the probabilities of maintaining programmatic viability is used as an example.

Motivating the Expert Panel--The Expert Panel on Programmatic Viability comprised senior-level managers from DOE and SNL. The scoring activity took place over a period of two consecutive days, with the first day devoted to the "motivating" and "structuring" stages of the process. On the first day, at the outset of the motivating stage, the session facilitators described in some detail the methodology that was being used for the comparative evaluation of the 34 options. This description, similar to that given in Section 2, included a discussion of the origin and role of programmatic viability in the decision tree. The next activity involved a fairly detailed review of the influence diagram for programmatic viability. The influence diagram had been developed previously by a subset of members of the Expert Panel on Programmatic Viability, as well as by other experts who were unable to attend the scoring session.

As previously indicated, the influence diagrams show the factors influencing the probability of failure to maintain programmatic viability, as the panel members found it easier to identify factors that would threaten the viability of the program, as opposed to factors that would aid in maintaining a viable program. The paths from those factors in the double-bubbles at the lowest level of the diagram to the highest-level bubble, representing the probability of failure to maintain program viability, were examined in some detail. A check was made with the panelists to determine whether additional factors in the diagram should be considered for discrimination between and among options.

Structuring--The structuring stage began after completing the review of the influence diagram (Figure 3-2). The panel members were provided with a graphical compilation of information for the 34 options relating to those factors in the diagram considered significant for purposes of discrimination. This compilation, shown in Figures 3-3 and 3-4, was prepared by selected members of expert panels or other members of the study task force with relevant expertise. The expert panel was directed to use the information as they saw fit, to supplement their own knowledge. The various columns shown in Figures 3-3 and 3-4 provided information on schedule (bubbles 18, 22 in Figure 3-2), cost (bubble 6), design difficulties (bubbles 24, 33, 34), expected NWTRB and NRC acceptability (bubble 23), residual uncertainty regarding the unsuitability of the site after characterization (bubble 17), and the probability of regulatory approval for repository construction/operation after characterization (bubbles 17, 18, 23). At this point, representatives from the design and testing Support groups presented detailed information on the geometrical layout, construction techniques and sequence, and early/late testing schedules for each of the 34 options. Subsequently, other technical representatives discussed the information in the remaining columns of the compilation.

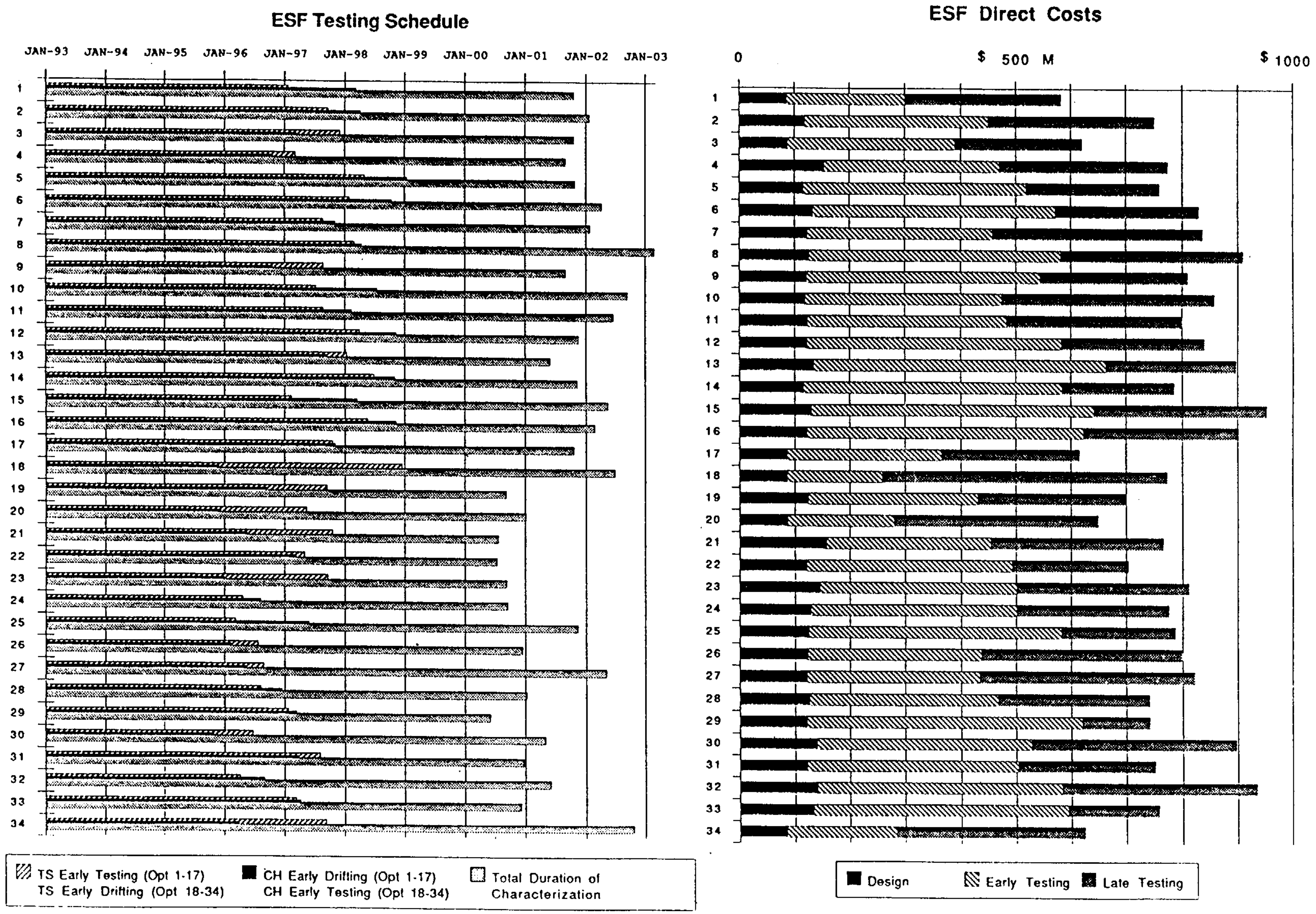

Figure 3-3. Compilation of Information Important To Discriminating Between and Among ESF Options From the Viewpoint of Programmatic Viability (Part 1)

Option	$ M/ month (average)	Compared to ESF original Title II Design (w/o CH), what is potential for: Design Dis-similarity?	Schedule Slippage in Re-Design?	What is potential for resolution of concerns by: NWTRB	NRC	Prob site not OK given "OK-ET","OK-LT" (%)	Probability of Regulatory Approval (%)	Option
1	4.6	🍎🍎	☹	●	☺	1.0	78	1
2	5.7	🍎🍎🍎🍎	☹☹	●●●	☺☺	0.7	93	2
3	4.9	🍎🍎🍎	☹	●	☺☺	0.8	89	3
4	6.2	🍎🍎🍎🍎	☹☹	●●●	☺☺☺	0.6	87	4
5	6.0	🍎🍎🍎🍎	☹☹	●●●	☺☺☺	0.7	85	5
6	6.2	🍎🍎🍎🍎	☹☹	●●●●	☺☺☺☺	0.8	93	6
7	6.4	🍎🍎🍎🍎	☹☹	●●●●	☺☺☺	0.8	92	7
8	6.3	🍎🍎🍎🍎	☹☹	●●●●●	☺☺☺	0.9	85	8
9	6.4	🍎🍎🍎🍎	☹☹	●●	☺☺	2.6	67	9
10	6.2	🍎🍎🍎🍎	☹☹	●●	☺☺	1.3	74	10
11	5.9	🍎🍎🍎🍎	☹☹	●●●	☺☺	0.9	83	11
12	6.5	🍎🍎🍎🍎	☹☹	●●●	☺☺☺	0.7	81	12
13	7.3	🍎🍎🍎🍎	☹☹	●●●●	☺☺☺☺	0.8	89	13
14	6.1	🍎🍎🍎🍎	☹☹	●●●	☺☺☺	0.7	78	14
15	7.1	🍎🍎🍎🍎🍎	☹☹☹☹	●●●	☺☺☺	0.5	95	15
16	6.8	🍎🍎🍎🍎🍎	☹☹☹☹	●●●	☺☺☺☺	0.6	90	16
17	4.8	🍎🍎	☹	●	☺☺	0.9	70	17
18	5.7	🍎🍎	☹☹	●	☺	1.0	77	18
19	6.1	🍎🍎🍎🍎	☹☹	●●●	☺☺	0.9	90	19
20	5.5	🍎🍎🍎	☹☹	●	☺☺	0.9	83	20
21	6.8	🍎🍎🍎🍎	☹☹	●●●	☺☺☺	0.8	84	21
22	6.3	🍎🍎🍎🍎	☹☹	●●●	☺☺☺	0.9	78	22
23	7.1	🍎🍎🍎🍎	☹☹	●●●●	☺☺☺☺	0.9	90	23
24	6.7	🍎🍎🍎🍎	☹☹	●●●●	☺☺☺	1.0	86	24
25	6.1	🍎🍎🍎🍎	☹☹	●●●●	☺☺☺	1.0	80	25
26	6.8	🍎🍎🍎🍎	☹☹☹☹	●●	☺☺	2.5	66	26
27	6.1	🍎🍎🍎🍎	☹☹☹☹	●●	☺☺	1.2	73	27
28	6.2	🍎🍎🍎🍎	☹☹	●●	☺☺	0.9	82	28
29	6.7	🍎🍎🍎🍎	☹☹	●●●	☺☺☺	0.9	79	29
30	7.4	🍎🍎🍎🍎	☹☹☹☹	●●●●	☺☺☺☺	0.8	87	30
31	6.4	🍎🍎🍎🍎	☹☹	●●	☺☺☺	0.9	77	31
32	7.5	🍎🍎🍎🍎🍎	☹☹☹☹	●●●	☺☺☺	0.7	94	32
33	6.4	🍎🍎🍎🍎🍎	☹☹☹☹	●●●	☺☺☺	0.7	88	33
34	4.5	🍎🍎	☹☹	●	☺☺	1.1	69	34

Figure 3-4. Compilation of Information Important to Discriminating Between and Among ESF Options From the Viewpoint of Programmatic Viability (Part 2)

The next activity in the structuring stage required that the panel members compare Options 2 through 34 against Option 1 (the base case), from the viewpoint of better or worse program viability. The rating form, shown in Figure 3-5, asked the question,

> "When compared to the ESF Base Case (Option 1), does this ESF option (i.e,. Options 2 through 34) offer a [much lower/lower/about the same/higher/much higher] likelihood for near-term success in maintaining a viable program, considering its (1) early/late testing schedule, (2) projected costs, (3) design dissimilarity and schedule slippage due to redesign requirements, (4) resolution of NWTRB and NRC concerns, (5) residual outcome of characterization testing, and (6) expected success with regulatory approval?"

Based on the information that had been provided during the day, as well as his own knowledge, each member of the panel was asked to complete the form after the close of the session and return it to the Decision Methodology Group prior to the start of the session on the second day.

Conditioning the Expert Panel for the Encoding Task--The session on the second day began with the "conditioning" stage of the scoring process. This stage involved steps that were designed to reduce common errors and biases in the assessment of judgmental probabilities (e.g., Tversky and Kahneman, 1974; 1981). Panelists were introduced to the theory of judgmental probability and apprised of the biases that have been shown to produce distortions in probability estimates. Panel members then practiced making probability estimates using a range of sample questions drawn from the World Almanac (for example, "What was the total production of pennies by the U.S. mint in 1988?"). Each question required a set of five answers from each panel member , representing the 1-, 25-, 50-, 75-, and 99-percent fractile for the cumulative probability distribution representing uncertainty in the accuracy of that person's answer. The probabilities estimated by each panel member were tabulated and compared with actual answers to the sample questions. This permitted each member to test his skill at assessing judgmental probabilities and provided an increased awareness of the need to avoid assessment biases, especially overconfidence. The goal of this exercise was to instruct panel members about how to estimate uncertainty accurately by providing a range of values likely to encompass the correct values. By demonstrating that

FORM FOR CONDUCTING THE OVERALL EVALUATION: PROBABILITY OF PROGRAM VIABILITY

When compared to the ESF Base Case (option 1), does this ESF option offer a ___________ likelihood for near-term success in maintaining a viable OCRWM program, considering its (1) early/late testing schedule, (2) projected costs, (3) design dis-similarity and schedule slippage due to re-design requirements, (4) resolution of NWTRB and NRC concerns, (5) residual outcome of characterization testing, and (6) expected success with regulatory approval? Choose one of the following:

much lower (ML), *lower* (L), about the *same* (S), *higher* (H), or *much higher* (MH)

[circle one].

Option	Range of Likelihood				
2	ML	L	S	H	MH
3	ML	L	S	H	MH
4	ML	L	S	H	MH
5	ML	L	S	H	MH
6	ML	L	S	H	MH
7	ML	L	S	H	MH
8	ML	L	S	H	MH
9	ML	L	S	H	MH
10	ML	L	S	H	MH
11	ML	L	S	H	MH
12	ML	L	S	H	MH
13	ML	L	S	H	MH
14	ML	L	S	H	MH
15	ML	L	S	H	MH
16	ML	L	S	H	MH
17	ML	L	S	H	MH
18	ML	L	S	H	MH
19	ML	L	S	H	MH
20	ML	L	S	H	MH
21	ML	L	S	H	MH
22	ML	L	S	H	MH
23	ML	L	S	H	MH
24	ML	L	S	H	MH
25	ML	L	S	H	MH
26	ML	L	S	H	MH
27	ML	L	S	H	MH
28	ML	L	S	H	MH
29	ML	L	S	H	MH
30	ML	L	S	H	MH
31	ML	L	S	H	MH
32	ML	L	S	H	MH
33	ML	L	S	H	MH
34	ML	L	S	H	MH

Figure 3-5. Form for Conducting a Qualitative Ranking of ESF Options From the Viewpoint of Programmatic Viability

individuals are prone to overconfidence, the exercise was expected to encourage the panelists to apply increased care in developing probability estimates. In addition, the use of a "probability wheel" as a reference lottery was demonstrated (Merkhofer, 1987a). Finally, glass bowls of black and white marbles were provided as reference lotteries of 1 chance in 10, 1 chance in 20, 1 chance in 50, 1 chance in 100, and 1 chance in 1000.

Encoding and Quantifying Judgments--The next stage in the scoring process was the actual quantification of the probability estimates for near-term success in maintaining a viable repository program for each of the 34 options. The compilation of the relative ranking of Options 2 through 34 against Option 1, as shown in Table 3-1, was distributed to the panel members. The ranking was established by assigning numerical values of -2, -1, 0, +1, +2, to ML (much lower), L (lower), S (about the same), H (higher), and MH (much higher), respectively, to the qualitative ratings from the panel members and arithmetically averaging the sum for each option. According to Table 3-1, Option 24 was judged on average and relative to Option 1 to have the most potential for maintaining a viable program. Conversely, Options 9, 15, and 16 exhibited, on average and relative to Option 1 the least potential. On average, Options 5, 11, 12, 17, and 18 were comparable to Option 1.

After reviewing the qualitative ranking, the panel members were asked to provide their high, best judgment, and low probability estimates, by individual ballot, for near-term success in maintaining a viable program in the event that Option 1 were to be selected for implementation at the Yucca Mountain site. The basis for establishing a high-probability estimate was explained to the panel as follows. Assume that 20 other panels of experts of comparable expertise and experience were convened and subjected to the same level of motivating, structuring, and conditioning as the current expert panel experienced. If the 20 panels were asked to provide a best-judgment estimate for near-term success in maintaining a viable program with Option 1, only one of those 20 panels would provide an estimate that was higher than the high estimate provided by the current expert panel. The basis for establishing a low-probability estimate was explained in the converse manner.

TABLE 3-1

QUALITATIVE RANKING OF ESF OPTIONS FROM THE VIEWPOINT OF PROGRAMMATIC VIABILITY

Ratings Compared to Option 1*									Options Ranked According to Highest Weighted Average	
Option	ML	L	S	H	MH	Number of Experts	Weighted Average		Option	Weighted Average
2	0	1	2	4	0	7	0.4		24	1.9
3	0	1	6	0	0	7	-0.1		23	1.6
4	0	0	2	4	1	7	0.9		25	1.4
5	1	1	3	1	1	7	0.0		30	1.4
6	0	0	3	3	1	7	0.7		7	1.0
7	0	0	1	5	1	7	1.0		13	1.0
8	0	1	3	3	0	7	0.3		19	1.0
9	1	2	3	1	0	7	-0.4		21	1.0
10	1	0	5	1	0	7	-0.1		28	1.0
11	0	1	5	1	0	7	0.0		29	1.0
12	0	2	3	2	0	7	0.0		4	0.9
13	0	0	2	3	2	7	1.0		22	0.9
14	0	2	4	1	0	7	-0.1		6	0.7
15	0	4	2	1	0	7	-0.4		20	0.6
16	1	2	3	1	0	7	-0.4		2	0.4
17	0	1	5	1	0	7	0.0		27	0.4
18	0	0	7	0	0	7	0.0		8	0.3
19	0	1	2	0	4	7	1.0		31	0.3
20	0	0	3	4	0	7	0.6		32	0.3
21	0	0	1	5	1	7	1.0		33	0.1
22	0	0	2	4	1	7	0.9		5	0.0
23	0	0	0	3	4	7	1.6		11	0.0
24	0	0	0	1	6	7	1.9		12	0.0
25	0	0	0	4	3	7	1.4		17	0.0
26	1	2	1	3	0	7	-0.1		18	0.0
27	1	1	1	2	2	7	0.4		3	-0.1
28	0	0	1	5	1	7	1.0		10	-0.1
29	0	0	1	5	1	7	1.0		14	-0.1
30	0	0	1	2	4	7	1.4		26	-0.1
31	0	1	3	3	0	7	0.3		34	-0.3
32	0	2	2	2	1	7	0.3		9	-0.4
33	0	2	3	1	1	7	0.1		15	-0.4
34	0	2	5	0	0	7	-0.3		16	-0.4

*ML = Much Lower
L = Lower
S = Same
H = Higher
MH = Much Higher

The probability estimates for Option 1 were compiled as shown in Figure 3-6 and reviewed by the panelists. The best-judgment probability estimates ranged from 0.25 to 0.80, with an arithmetic average of 0.59. The high-probability estimates ranged from 0.33 to 0.98, with the second-highest estimate being 0.95. The low-probability estimates ranged from 0.05 to 0.50, with the second-lowest estimate being 0.12. The second-highest high probability and the second-lowest low probability were selected for purposes of discussion in order to moderate extreme judgmental views. After the panel members discussed the various rationales for arriving at the individual estimates, they decided to cast a second ballot. The estimates from this second ballot are shown in Figure 3-7. As illustrated, the range between high and low estimates tended to expand (representing greater uncertainty) and the differences of opinion among the experts tended to decrease. The average of the best-judgment probability estimates decreased slightly to 0.54. After considerable discussion, the panelists decided by consensus that the best-judgment probability estimate should be 0.55, and that the high and low estimates should be 0.90 and 0.10, respectively, for Option 1.

By the same process of balloting and discussion, the panel established the three consensus probability estimates for Option 24. At this point, the members of the panel were asked to provide, by individual ballot, the probability estimates for the remaining 32 options. These estimates were compiled, the arithmetic averages calculated, the second-highest high and second-lowest low selected, and the results provided to the panel in tabulated form.

<u>Resolving Differences Among Panel Members</u>--At this point in the scoring process, an attempt was made to clarify and resolve differences of opinion between and among panel members, and to evaluate the reasonableness of the judgments of the panelists. During the course of the discussions and exchange of opinions, panel members were asked whether they could agree to some set of probability estimates for the remaining options, with the averages proposed as a starting position for seeking a consensus. One member declared that he could not accept any set of probabilities near the averages. This member was offered, and accepted, the opportunity to submit his probability estimates in the form of a minority report. The probability estimates of the remaining six members were then compiled, the arithmetic averages calculated, and the results presented in tabulated form. The ranking of the options in terms of decreasing probabilities, as well as the magnitudes and ranges of the probabilities, were examined and discussed in relation to the various features of the options. For various selected

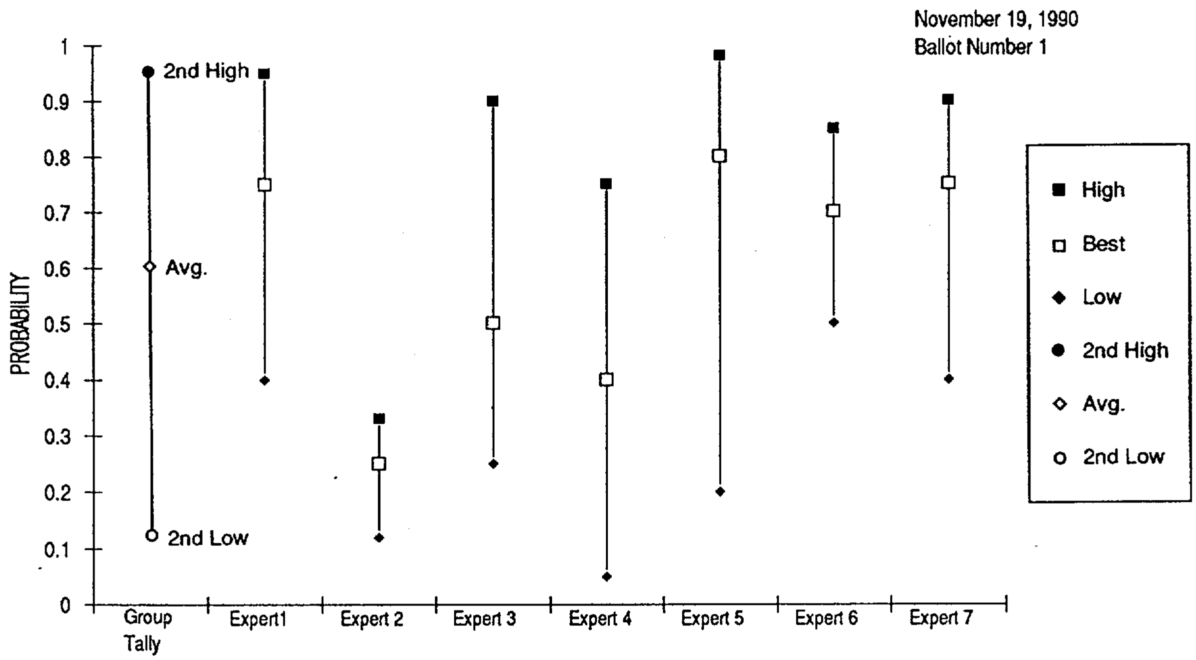

Figure 3-6. Probability Estimates From the First Ballot by the Expert Panel on Programmatic Viability for ESF Option 1 (Base Case)

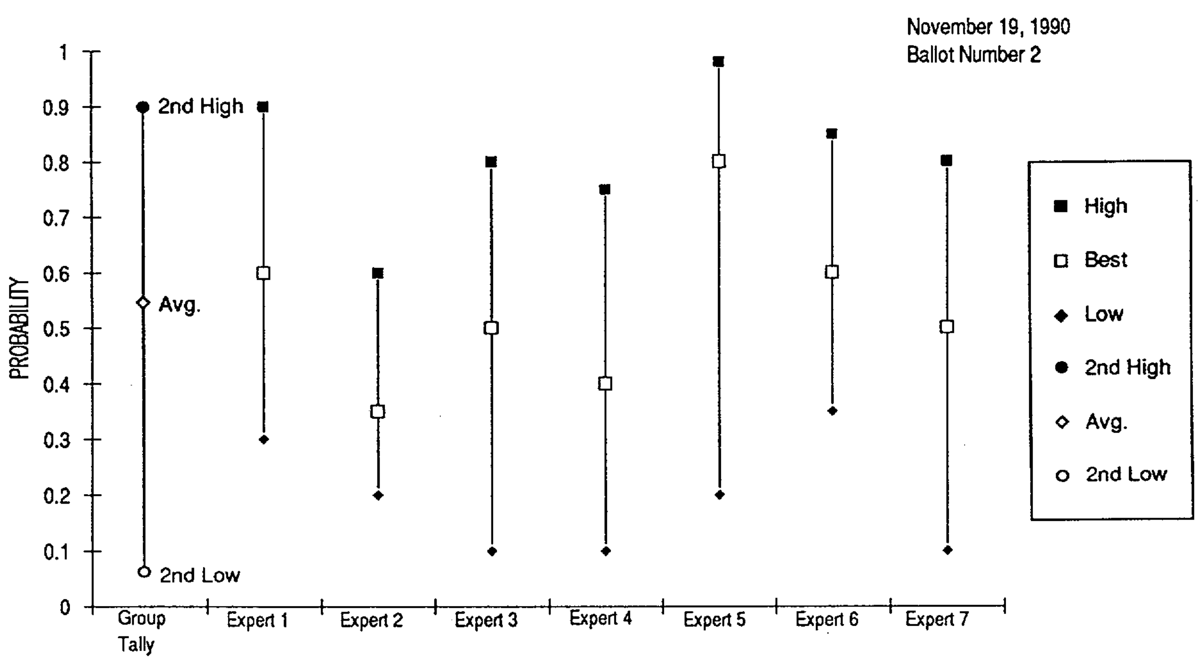

Figure 3-7. Probability Estimates From the Second Ballot by the Expert Panel on Programmatic Viability for ESF Option 1 (Base Case)

options, the variation in probability estimates among panel members was evaluated in relation to the basis for the judgments.

Generating and Verifying the Consensus Probability Estimates--After considerable interchange of views and opinions, accompanied by minor adjustments in a few of the probabilities, the remaining six members of the Panel agreed, by consensus, on a set of probability estimates for the majority report of the Expert Panel on Programmatic Viability, and recommended that this set of estimates be used in the comparative evaluation of the 34 options. These deliberations and agreements constituted the final stage of the probability encoding process for programmatic viability.

3.1.3 Concluding Remarks

The encoding process, as described above, was used to obtain all of the probabilities that were required in the decision tree and Nature's Tree. The only significant difference between the process used for the other probabilities and that described above related to the structuring stage. As indicated above, members of the Design and Testing Support Group provided a set of displays (Figures 3-3 and 3-4) to summarize the relative performance of the options with respect to double-bubbled (discriminating) factors in the influence diagram for programmatic viability. A different process was used when members of the expert panels themselves (rather than members of the Design and Testing Support Group) were better able to provide assessments of options with respect to the double-bubbled factors.

Thus for example, in the case of the testing probabilities, regulatory approval probabilities, and closure probabilities, panel members were asked to systematically compare the options with respect to each lowest-level, double-bubbled factor in the relevant influence diagram. To facilitate this process, instruction workbooks (contained in the records package, see Appendix D) were provided that directed each panel member to compare Options 2 through 34 with Option 1, one at a time, and express a judgment as to whether that option would perform much worse, worse, about the same, better, or much better than the Option 1 with respect to each lowest-level, double-bubbled factor. These individual judgments helped to ensure that each panel member had thought through thoroughly the considerations relevant to comparing the options with respect to the top-level bubble in the influence diagram and, therefore, provided a basis for each panel member to express an overall judgment about each option.

Although considerable effort was made to resolve differences in judgments among members of each expert panel, it was not possible in all instances to obtain consensus agreement on a single set of probability estimates. In such cases, as illustrated above for the case of programmatic viability, the opportunity to submit a minority report was offered to, and always accepted by, the dissenting member or members of an expert panel.

3.2 Presentation and Discussion of Results

The assessment process described above was used to provide a set of high, best-judgment, and low probability estimates for each of the eight probabilities in Nature's Tree and the decision tree. The consensus probability estimates that were agreed upon by the majority of panel members were referred to as majority reports, and provided the basis for a nominal analysis. In addition to these majority, or nominal, estimates, four minority reports regarding specific probability estimates were submitted. Minority reports consist of the consensus probability estimates provided by subsets of panels composed of one or more experts who could not agree with the majority opinion.

In addition to the four minority report probability estimates, two additional reports were provided to reflect minor changes in some options. After the completion of the encoding process, the extent of drifting in the CH unit during the "early testing" phase of characterization was revised slightly by the Design and Testing Support Group for Options 4, 15, and 16. The Decision Methodology Group requested and received a report from one member of the Expert Panel on Characterization Testing that provided revised testing probabilities. The revisions consisted of alternative probabilities for early false negative and early false positive outcomes for the three affected options. There were, therefore, a total of 14 sets of probability estimates (eight nominal estimates and six minority reports) for the eight performance measures. The various majority- and minority-report probability estimates provided by the various panels are summarized in the following sections.

As will be apparent in the discussion that follows, the probability estimates provided in majority and minority reports typically did not differ substantially from option to option. For example, differences between closely ranked options might differ by only a percentage point (e.g., 80 percent probability compared to 81 percent probability), or less. The question of whether such small differences reflected real distinctions as perceived by the expert panels was an important one. In all probability assessment sessions, panel members were instructed to assign the same probability numbers to two options unless the panel believed that one option was inferior or superior with respect to the measure in question. Although panel members often had difficulty determining the absolute magnitude of the probability to assign, they found it easier to make relative judgments regarding whether one option was superior or inferior to another according to a specified probability measure. Thus, the small differences in probability estimates provided by panels for the various options reflected real distinctions in the judgments of the expert panels.

3.2.1 Characterization Testing

The probability estimates for an early false negative, a late false negative, an early false positive, and a late false positive outcome for the 34 options are presented in Tables 3-2 through 3-5. These estimates were obtained from the Expert Panel on Characterization Testing. As mentioned above, minority reports for the testing probabilities were solicited from one member of the expert panel after conclusion of the process because of slight revisions in the expected drifting in the CH unit during the "early phase" of characterization testing for three options. For Options 4, 15, and 16, the minority reports provided revised estimates of 0.12, 0.16, and 0.14, respectively, for the probability of an early false negative, and 0.16, 0.20, and 0.18, respectively, for the probability of an early false positive. The probability estimates for the rest of the options remained the same as given in the majority report.

For the purpose of interpreting the results in relation to the features of the options, it should be kept in mind that the following factors were considered to be significant for discriminating between and among options from the viewpoint of the outcome of characterization testing (as illustrated by the double-bubbled factors in the influence diagrams in Appendix B, Figures B-2 through B-6):

- Construction method using drill-and-blast versus mechanical mining (all probabilities);

- SCP tests not included in the "early" test suite leading to inadequate characterization of the CH unit or the TS unit (probabilities of an early false negative and an early false positive);

TABLE 3-2

MAJORITY-REPORT PROBABILITIES FOR AN EARLY FALSE NEGATIVE OUTCOME DURING CHARACTERIZATION TESTING

	Probabilities		
ESF Option	Low	Best Judgment	High
1	0.01	0.14	0.60
2	0.01	0.13	0.60
3	0.01	0.13	0.60
4	0.01	0.13	0.60
5	0.01	0.13	0.60
6	0.01	0.14	0.60
7	0.01	0.14	0.60
8	0.01	0.14	0.60
9	0.01	0.23	0.80
10	0.01	0.19	0.75
11	0.01	0.14	0.60
12	0.01	0.13	0.60
13	0.01	0.12	0.60
14	0.01	0.13	0.60
15	0.01	0.14	0.60
16	0.01	0.16	0.65
17	0.01	0.14	0.60
18	0.01	0.15	0.70
19	0.01	0.13	0.60
20	0.01	0.14	0.70
21	0.01	0.12	0.60
22	0.01	0.12	0.60
23	0.01	0.14	0.60
24	0.01	0.14	0.60
25	0.01	0.14	0.60
26	0.01	0.23	0.80
27	0.01	0.18	0.75
28	0.01	0.14	0.60
29	0.01	0.13	0.60
30	0.01	0.12	0.60
31	0.01	0.13	0.60
32	0.01	0.17	0.75
33	0.01	0.14	0.60
34	0.01	0.13	0.60

TABLE 3-3

MAJORITY-REPORT PROBABILITIES FOR A LATE FALSE NEGATIVE OUTCOME DURING CHARACTERIZATION TESTING

ESF Option	Probabilities Low	Best Judgment	High
1	0.01	0.11	0.40
2	0.01	0.09	0.40
3	0.01	0.09	0.40
4	0.01	0.08	0.40
5	0.01	0.09	0.40
6	0.01	0.10	0.40
7	0.01	0.09	0.40
8	0.01	0.10	0.40
9	0.01	0.15	0.60
10	0.01	0.10	0.40
11	0.01	0.09	0.40
12	0.01	0.09	0.40
13	0.01	0.09	0.40
14	0.01	0.09	0.40
15	0.01	0.09	0.40
16	0.01	0.10	0.40
17	0.01	0.09	0.40
18	0.01	0.12	0.40
19	0.01	0.11	0.40
20	0.01	0.11	0.40
21	0.01	0.09	0.40
22	0.01	0.10	0.40
23	0.01	0.11	0.40
24	0.01	0.10	0.40
25	0.01	0.10	0.40
26	0.01	0.16	0.60
27	0.01	0.11	0.40
28	0.01	0.09	0.40
29	0.01	0.10	0.40
30	0.01	0.09	0.40
31	0.01	0.10	0.40
32	0.01	0.10	0.40
33	0.01	0.10	0.40
34	0.01	0.11	0.40

TABLE 3-4

MAJORITY-REPORT PROBABILITIES FOR AN EARLY FALSE POSITIVE OUTCOME DURING CHARACTERIZATION TESTING

	Probabilities		
ESF Option	Low	Best Judgment	High
1	0.05	0.25	0.80
2	0.04	0.20	0.80
3	0.03	0.19	0.80
4	0.03	0.17	0.60
5	0.04	0.21	0.80
6	0.04	0.22	0.80
7	0.04	0.21	0.80
8	0.04	0.21	0.80
9	0.05	0.35	0.90
10	0.05	0.27	0.85
11	0.04	0.20	0.80
12	0.04	0.21	0.80
13	0.03	0.18	0.65
14	0.04	0.21	0.80
15	0.03	0.18	0.75
16	0.03	0.20	0.80
17	0.04	0.20	0.80
18	0.04	0.24	0.81
19	0.04	0.21	0.80
20	0.04	0.22	0.80
21	0.03	0.20	0.80
22	0.04	0.21	0.80
23	0.04	0.23	0.80
24	0.04	0.22	0.80
25	0.04	0.20	0.80
26	0.05	0.34	0.95
27	0.04	0.23	0.80
28	0.04	0.20	0.80
29	0.04	0.20	0.80
30	0.03	0.19	0.65
31	0.04	0.20	0.80
32	0.04	0.20	0.80
33	0.04	0.20	0.80
34	0.05	0.24	0.81

TABLE 3-5

MAJORITY-REPORT PROBABILITIES FOR A LATE FALSE POSITIVE OUTCOME DURING CHARACTERIZATION TESTING

ESF Option	Probabilities: Low	Best Judgment	High
1	0.05	0.60	0.90
2	0.05	0.55	0.90
3	0.05	0.66	0.95
4	0.05	0.51	0.90
5	0.05	0.52	0.90
6	0.05	0.59	0.90
7	0.05	0.59	0.90
8	0.05	0.62	0.95
9	0.05	0.68	0.90
10	0.05	0.67	0.90
11	0.05	0.60	0.95
12	0.05	0.51	0.90
13	0.05	0.72	0.99
14	0.05	0.53	0.90
15	0.05	0.55	0.90
16	0.05	0.51	0.90
17	0.05	0.63	0.90
18	0.05	0.61	0.90
19	0.05	0.63	0.90
20	0.05	0.62	0.90
21	0.05	0.58	0.90
22	0.05	0.66	0.95
23	0.05	0.66	0.95
24	0.05	0.67	0.95
25	0.05	0.72	0.95
26	0.05	0.65	0.95
27	0.05	0.70	0.95
28	0.05	0.63	0.95
29	0.05	0.66	0.95
30	0.05	0.76	0.99
31	0.05	0.67	0.95
32	0.05	0.64	0.95
33	0.05	0.63	0.95
34	0.05	0.59	0.90

- SCP tests not included in the "late" test suite leading to inadequate characterization of the CH unit or the TS unit (probabilities of a late false negative and a late false positive);

- Number and location of shafts versus ramps, and location representativeness, as related to the inability to design or conduct natural barrier tests (all probabilities);

- Inadequate duration of early tests (probabilities of a late false negative and a late false positive);

- Inadequate physical space for test flexibility (probability of a late false negative); and

- Late testing in degraded rock conditions as related to the inability to characterize the CH unit or the rock units above the CH unit (probability of a late false negative).

An evaluation of the results in Tables 3-2 through 3-5 shows that Options 2, 4, 5, 6, 7, 8, 11, 12, 14, 15, and 21 were judged to have probabilities that were less than, or about equal to, the average probabilities for all four measures that deal with the outcome of characterization testing. That is, as compared to the remaining options, these eleven options exhibit design and testing features that enhance testing accuracy. The principal features of this suite of options include:

- Apart from Option 21, all of the options emphasize early testing in the TS unit together with early drifting in the CH unit.

- Apart from Option 6, which has two access ramps only, all of the options have at least one access shaft in conjunction with one access ramp.

- Apart from Option 6, in which the two access ramps are constructed with tunnel boring machines, eight of the ten remaining options have shafts that are constructed by the drill-and-blast techniques, with the shafts in the other two options constructed with a boring machine and a V-Mole.

- All of the options have a raised-bored internal shaft connecting the TS unit with the CH unit, and, with the exception of Options 6 and 15, the construction of these shafts is completed before the end of the early testing phase.

- Eight of the options have the MTL located in the northeast area of the block, and three have the MTL located at the south end.

- The MTLs are constructed by the drill-and-blast technique in five of the options, and by mechanical mining in the remaining six options.

Further evaluation of the results in Tables 3-2 through 3-5 shows that Options 9, 10, 26, and 27 were judged to have probabilities that were greater than, or about equal to, the average probabilities for all four measures. That is, as compared to the other thirty options, these four options exhibit design and testing features that would yield less accuracy in characterization testing. These options have one access shaft and one access ramp, with the shafts constructed by a raise-boring machine or a blind-boring machine. These construction techniques were considered by the panelists to provide essentially no opportunity for examination and testing of the rock units during the actual excavation process.

Options 3, 13, 17, 22, 24, 25, 28, 29, 30, 31, and 33 were judged to have a probability of late false positive greater than, or about equal to, the average probability for that measure, but less than, or about equal to, the average probabilities for the other three measures. That is, these options were judged to provide relatively poor testing accuracy as related to a late false positive, but relatively good testing accuracy according to the other three measures. Eight of these eleven options emphasize early testing in the CH unit. Although seven of these options feature an access shaft in conjunction with an access ramp, testing in the shafts or ramps during construction would be minimized in scope and duration. This situation could conceivably result in missing an important adverse feature, or not being able to adequately characterize an identified feature at a later date because of degraded site conditions. Options 3 and 17 have two access shafts each, but no ramp, which would not allow even a cursory examination of the rock units outside the north end of the block. Options 13 and 30 have two access ramps each, but no shaft, which would not allow examination of the rock units in the main part of the block above the TS unit.

In addition to the minority report reflecting the revision to drifting in the CH unit, a minority report for the probabilities of an early false negative was submitted by two members of the Expert Panel. These two individuals felt that an alternative view regarding false negatives had merit. Specifically, the minority report provided by these individuals reflects a hypothesis that the probability of an early false negative is directly proportional to the amount of rock that is exposed by shafts, ramps, and drifts during the early phase of characterization. The probability estimates from this group of two experts are provided in Table 3-6. To demonstrate their disagreement with the view of these two panel members, the other seven members of the panel decided to submit their own minority report for the probability of an early false negative. These estimates, as shown in Table 3-7, reflect, for the most part, greater optimism about the accuracy of the results from early testing.

In summary, the testing accuracy of an option was estimated to be enhanced when that option featured

- Early testing in the TS unit together with early drifting in the CH unit,

- An access ramp in conjunction with one or more access shafts that are constructed by the drill-and-blast method or by a mechanical method that permits periodic examination of the wall rock and minimizes the use of water, and

- A raise-bored internal shaft that connects the TS unit with the CH unit and is completed during the early testing phase.

Conversely, the testing accuracy of an option was considered to be comparatively poor when that option featured

- Shaft construction with a blind-boring machine, which has the potential for introducing large quantities of water into the rock units and thereby hampering or denying adequate characterization, and

- Absence of a ramp, which does not permit examination of the rock units outside the repository block.

TABLE 3-6

MINORITY-REPORT (2 EXPERTS) PROBABILITIES FOR AN EARLY FALSE NEGATIVE OUTCOME DURING CHARACTERIZATION TESTING

ESF Option	Probabilities: Low	Best Judgment	High
1	0.01	0.14	0.60
2	0.01	0.18	0.70
3	0.02	0.25	0.73
4	0.02	0.28	0.73
5	0.02	0.23	0.70
6	0.01	0.20	0.65
7	0.01	0.21	0.65
8	0.01	0.21	0.65
9	0.01	0.19	0.60
10	0.01	0.19	0.60
11	0.01	0.21	0.65
12	0.02	0.23	0.70
13	0.02	0.23	0.70
14	0.01	0.22	0.70
15	0.01	0.20	0.65
16	0.01	0.20	0.60
17	0.01	0.19	0.70
18	0.01	0.15	0.60
19	0.01	0.19	0.70
20	0.01	0.16	0.65
21	0.02	0.21	0.73
22	0.02	0.23	0.70
23	0.01	0.21	0.65
24	0.01	0.20	0.65
25	0.01	0.20	0.65
26	0.01	0.19	0.58
27	0.01	0.20	0.60
28	0.01	0.21	0.65
29	0.01	0.22	0.70
30	0.02	0.25	0.73
31	0.02	0.23	0.70
32	0.01	0.19	0.60
33	0.01	0.20	0.65
34	0.01	0.16	0.65

TABLE 3-7

MINORITY-REPORT (7 EXPERTS) PROBABILITIES FOR AN EARLY FALSE NEGATIVE OUTCOME DURING CHARACTERIZATION TESTING

ESF Option	Probabilities Low	Best Judgment	High
1	0.01	0.14	0.60
2	0.01	0.12	0.60
3	0.01	0.10	0.60
4	0.01	0.09	0.60
5	0.01	0.10	0.60
6	0.01	0.12	0.60
7	0.01	0.13	0.60
8	0.01	0.12	0.60
9	0.02	0.24	0.80
10	0.01	0.19	0.75
11	0.01	0.12	0.60
12	0.01	0.10	0.60
13	0.01	0.09	0.60
14	0.01	0.11	0.60
15	0.01	0.13	0.60
16	0.01	0.15	0.65
17	0.01	0.12	0.60
18	0.01	0.15	0.70
19	0.01	0.12	0.60
20	0.01	0.13	0.60
21	0.01	0.09	0.60
22	0.01	0.10	0.60
23	0.01	0.12	0.60
24	0.01	0.13	0.60
25	0.01	0.12	0.60
26	0.03	0.24	0.80
27	0.01	0.18	0.75
28	0.01	0.12	0.60
29	0.01	0.10	0.60
30	0.01	0.08	0.60
31	0.01	0.10	0.60
32	0.01	0.17	0.75
33	0.01	0.13	0.60
34	0.01	0.12	0.60

3.2.2 Prior Probability That the Site Is OK

The prior probability estimates that the site is OK for each of the 34 options and associated repository configurations are presented in Table 3-8 (see Section 2.3 for definition of Site is OK). The estimates were generated by the Expert Panel on Postclosure Health and reflected the level of confidence that the site, in conjunction with particular ESF-repository configurations, would meet the EPA standard which, as explained in Section 2, is expressed in terms of probabilities of exceeding specified release limits. The magnitudes of, and range in, the best-judgment probability estimates are quite high, with a variation from a high of 96 percent to a low of 93 percent. The high-probability estimate of 99.9 percent was judged to be effectively insensitive to variations in features between and among the options. Apart from Options 9 and 26, such was also the situation for the constant low-probability estimate of 75 percent.

The estimated best-judgment prior probabilities varied from option to option because of variations in the characteristics and features of the various options that affect the level of anticipated releases and, therefore, the probability that the site is OK. Specifically, the following four factors were identified to be the most significant discriminators for this measure (as identified by the lowest-level double-bubbled factors in the influence diagram in Figure B-13):

- Repository location in terms of the distance from the emplacement horizon to the water table, including the potential for water-table rise;

- Number, type, and location of ESF and repository accesses (shafts versus ramps), including the nature and extent of penetration into the CH unit;

- Repository configuration insofar as the waste emplacement drifts intersect the Ghost Dance Fault; and

- Fluid and material usage during ESF construction.

TABLE 3-8

MAJORITY-REPORT PROBABILITIES THAT THE SITE IS OK

ESF Option	Probabilities: Low	Best Judgment	High
1	0.750	0.950	0.999
2	0.750	0.950	0.999
3	0.750	0.950	0.999
4	0.750	0.945	0.999
5	0.750	0.950	0.999
6	0.750	0.955	0.999
7	0.750	0.950	0.999
8	0.750	0.950	0.999
9	0.700	0.930	0.999
10	0.750	0.950	0.999
11	0.750	0.945	0.999
12	0.750	0.950	0.999
13	0.750	0.955	0.999
14	0.750	0.950	0.999
15	0.750	0.960	0.999
16	0.750	0.960	0.999
17	0.750	0.945	0.999
18	0.750	0.950	0.999
19	0.750	0.950	0.999
20	0.750	0.950	0.999
21	0.750	0.945	0.999
22	0.750	0.950	0.999
23	0.750	0.955	0.999
24	0.750	0.950	0.999
25	0.750	0.950	0.999
26	0.700	0.930	0.999
27	0.750	0.950	0.999
28	0.750	0.945	0.999
29	0.750	0.950	0.999
30	0.750	0.955	0.999
31	0.750	0.950	0.999
32	0.750	0.960	0.999
33	0.750	0.960	0.999
34	0.750	0.945	0.999

Other factors of lesser significance included

- ESF and repository construction methods,
- ESF type,
- ESF connection with the repository, and
- Rock support system in the repository.

This combination of factors, including others considered to be of little or no significance for the purpose of discriminating between and among options, influences changes in the disposal system and the post-waste-emplacement characteristics of the engineered barrier system (EBS) and seals. These changes in turn would influence gas-phase and groundwater transport through the EBS, seals, unsaturated zone, saturated zone, and, finally, releases to the accessible environment. Waste-package lifetime, as well as the magnitude and rate of radionuclide releases from the package, were considered only in a qualitative sense. That is, the presence of water in the vicinity of waste packages in greater abundance than expected for Option 1 could conceivably result in shorter package lifetimes and larger magnitudes or higher rates of release. However, these expectations were not quantified.

Table 3-8 shows that Options 15, 16, 32, and 33 were judged by the panel to have the highest best-judgment prior probabilities (96 percent) that the site is OK. These four options are characterized by three offset emplacement areas on two levels in the TS unit. The distance from the emplacement area to the water table, particularly in the northeast corner, is greater for these options than for any of the other 30 options. This additional separation distance would increase correspondingly the radionuclide transport time to the water table. These options also feature a single shaft from the surface to the CH unit, as well as emplacement drifts that do not intersect the Ghost Dance Fault.

Options 6, 13, 23, and 30 were judged to have the second highest prior probability (95.5 percent) that the site is OK. Although the emplacement drifts do intersect the Ghost Dance Fault in these options, there are no direct connections by virtue of vertical shafts from the surface to the CH unit. The principal means of access to both the TS and CH units is ramps. This feature effectively negates the potential for introduction of water from the surface to the emplacement horizon through the shaft seals, and then directly into the CH unit.

Options 9 and 26 were judged to have the lowest best-judgment prior probability (93 percent) that the site is OK. These options feature an access shaft constructed with the blind-boring technique, in conjunction with an access ramp and emplacement drifts that intersect the Ghost Dance Fault. The amount of water introduced into the rock units by the shaft construction technique could conceivably saturate the rock from the surface to the CH unit in the vicinity around the shaft. This situation could potentially create a pathway for enhanced water influx from the surface to the TS unit, and, subsequently, radionuclide transport into the CH unit.

Options 4, 11, 17, 21, 28, and 34 were judged to have the second lowest probability (94.5 percent) that the site is OK. Options 4, 17, 21, and 34 each have two direct connections from the surface to the CH unit by virtue of access shafts. In addition, Options 4 and 21 have an internal shaft, connecting the TS unit with the CH unit, in near vicinity to an access ramp and one of the access shafts. Options 17 and 34 feature waste-emplacement drifts that intersect the Ghost Dance Fault in conjunction with the tuff ramp at the south end of the repository block. Options 11 and 28 feature a shaft from the surface to the CH unit and an internal shaft connecting the TS unit to the CH unit, as well as waste-emplacement drifts that intersect the Ghost Dance Fault. The two shafts are located in the north end of the block, in near vicinity to an access ramp from the east and the tuff ramp from the north. The types, combinations, and locations of accesses in these options conceivably could increase the potential for water influx into the TS unit and transport into the CH unit.

In summary, the likelihood that the site would meet the EPA standard was considered to be comparatively high when the associated ESF-repository configuration featured

- Offset emplacement areas on two levels so that the separation distance between the emplacement areas and water table would be increased, which in turn would increase the radionuclide travel time between the waste and the water table; and

- Absence of a shaft that would directly connect the CH unit with the surface, thereby effectively negating the potential for introduction of water from the surface to the emplacement horizon and, subsequently, into the CH unit.

The level of confidence that the site would meet the EPA standard decreased somewhat, but not substantially, when the ESF-repository configuration exhibited the following features:

- Shaft construction with a blind-boring machine, which would have the potential for saturating the rock from the surface to the CH unit in the vicinity of the shaft; and

- Emplacement drifts that would intersect the Ghost Dance Fault, thereby introducing a potential pathway for radionuclide travel to the water table.

Tables 3-9 and 3-10 show two key results of analyzing the majority report on testing and prior probabilities. Table 3-9 provides the probabilities of "OK" results from testing, computed using Equations 2-6 and 2-7 in Section 2. These probabilities were needed for the decision tree. Table 3-10 provides the residual probabilities that the site is NOT OK, even though testing concludes that it is "OK." These probabilities were needed as input for the assessment of the probabilities of regulatory approval and repository closure.

3.2.3 Regulatory Approval

The probability estimates for regulatory approval of the proposed construction and operation of the repository for the 34 options are presented in Table 3-11. The estimates were obtained from the Expert Panel on Regulatory Considerations and represent the level of confidence felt about obtaining the necessary approvals and authorizations from the DOE, the NRC, the President, and the Congress for the construction and operation of a repository at the Yucca Mountain site. The best-judgment probabilities range from a low of 66 percent to a high of 95 percent. The high probability estimates range between 94 percent and 99 percent. For the low probabilities, the panel judged that the best options had only a 50:50 chance for regulatory approval, while the worst options had only one chance in four.

According to the influence diagram in Appendix B, Figure B-10, the likelihood of regulatory approval is influenced by factors related to either "technical confidence" or "procedural confidence". Procedural confidence is influenced principally by the

TABLE 3-9

CHARACTERIZATION TESTING PROBABILITIES ON THE ESF DECISION TREE

ESF Option	Prob ("OK-ET")	Prob ("OK-LT" | "OK-ET")
1	0.83	0.89
2	0.83	0.91
3	0.83	0.90
4	0.83	0.92
5	0.84	0.90
6	0.83	0.90
7	0.82	0.90
8	0.83	0.90
9	0.74	0.84
10	0.78	0.89
11	0.82	0.90
12	0.84	0.90
13	0.85	0.91
14	0.84	0.90
15	0.83	0.90
16	0.81	0.89
17	0.83	0.90
18	0.82	0.88
19	0.83	0.89
20	0.83	0.89
21	0.84	0.90
22	0.84	0.90
23	0.83	0.89
24	0.82	0.89
25	0.83	0.90
26	0.74	0.83
27	0.79	0.89
28	0.83	0.90
29	0.84	0.90
30	0.85	0.91
31	0.84	0.90
32	0.80	0.90
33	0.83	0.90
34	0.83	0.89

TABLE 3-10

RESIDUAL PROBABILITY THAT THE SITE IS NOT OK

ESF Option	Prob (NOT OK | "OK-ET","OK-LT")
1	0.010
2	0.007
3	0.008
4	0.006
5	0.007
6	0.008
7	0.008
8	0.009
9	0.026
10	0.013
11	0.009
12	0.007
13	0.008
14	0.007
15	0.005
16	0.006
17	0.009
18	0.010
19	0.009
20	0.009
21	0.008
22	0.009
23	0.009
24	0.010
25	0.010
26	0.025
27	0.012
28	0.009
29	0.009
30	0.008
31	0.009
32	0.007
33	0.007
34	0.011

TABLE 3-11

MAJORITY-REPORT PROBABILITIES FOR REGULATORY APPROVAL

ESF Option	Probabilities: Low	Best Judgment	High
1	0.45	0.78	0.96
2	0.50	0.93	0.99
3	0.50	0.89	0.98
4	0.50	0.87	0.98
5	0.47	0.85	0.98
6	0.50	0.93	0.99
7	0.50	0.92	0.98
8	0.47	0.85	0.98
9	0.25	0.67	0.95
10	0.40	0.74	0.96
11	0.45	0.83	0.97
12	0.45	0.81	0.97
13	0.50	0.89	0.99
14	0.40	0.78	0.96
15	0.50	0.95	0.99
16	0.49	0.90	0.99
17	0.35	0.70	0.95
18	0.45	0.77	0.96
19	0.50	0.90	0.99
20	0.45	0.83	0.97
21	0.45	0.84	0.97
22	0.44	0.78	0.96
23	0.50	0.90	0.99
24	0.47	0.86	0.97
25	0.45	0.80	0.97
26	0.25	0.66	0.95
27	0.40	0.73	0.96
28	0.45	0.82	0.97
29	0.45	0.79	0.96
30	0.50	0.87	0.99
31	0.40	0.77	0.96
32	0.50	0.94	0.99
33	0.48	0.88	0.98
34	0.25	0.69	0.94

"estimated degree of compliance with procedural requirements," which, in turn, is influenced most significantly by

- Early tests for site suitability,
- Capability for extended duration tests, and
- Potential for allowing a high-level waste test.

On the other hand, technical confidence is influenced most significantly by three factors that had been quantified previously by other expert panels:

- Consequence estimates for environmental impacts during preclosure (aesthetics and historical properties),

- Consequence estimates for radionuclide releases to the accessible environment during postclosure, and

- The residual probability that the site is NOT OK even though the outcome of both early and late characterization testing indicates that it is "OK."

Option 15, judged to have the highest probability of regulatory approval, was computed to have the lowest residual probability that the site is NOT OK (Table 3-10), and also to have the second-to-the-lowest releases of radionuclides by aqueous transport. (See Section 4.2.1.) This option features three offset waste-emplacement areas on two levels, with increased separation distance between the waste and the water table. In addition, this option places primary emphasis on early testing of the TS unit, with access to the underground by means of a shaft constructed by the drill-and-blast method and a ramp constructed with a tunnel-boring machine. Option 32, judged to have the second-highest probability of approval, is basically identical to Option 15, except that the primary emphasis is placed on early testing of the CH unit. Conversely, Option 26, ranked relatively the worst for regulatory approval, was the lowest-ranked option on releases and next-to-the-lowest ranked option on residual probability. This option places primary emphasis on early CH testing and features a shaft that is constructed by the blind-boring method. Options 15, 26, and 32 have relatively few aesthetic impacts, but exhibit a high level of impact on historical properties.

In summary, the factors that implicitly would influence most favorably the likelihood of regulatory approval were those that explicitly would influence greater accuracy in characterization testing and a relatively lower potential for radionuclide releases from the waste to the water table. These factors were

- Early testing in the TS unit together with early drifting in the CH unit;

- An ESF design that would feature

  An access ramp in conjunction with one or more access shafts constructed by the drill-and-blast method or by a mechanical method that would permit periodic examination of the wall rock and minimize the use of water;

  A raise-bored internal shaft that would connect the TS unit with the CH unit and be completed during the early testing phase; and

  The absence of a shaft that would directly connect the CH unit with the surface, thereby effectively negating the potential for introduction of water from the surface to the emplacement horizon and, subsequently, into the CH unit; and

- A repository design that would feature offset emplacement areas on two levels, for a greater separation distance between the emplacement areas and the water table, which would increase the radionuclide travel time from the waste to the water table.

3.2.4 Repository Closure

The estimates for the probability of repository closure for the 34 options are presented in Table 3-12. The estimates represent the majority report from the Expert Panel on Regulatory Considerations and represent the level of confidence in obtaining authorization to decommission and permanently close the repository at the end of the caretaker period. The best-judgment probabilities are exceptionally high and range from a low of 99 percent to a high of 99.9 percent. A minority report was provided by one panelist. The minority report provides a best-judgment estimate of 99 percent for the probability of repository closure; that is, there is only 1 chance in 100 that the waste will be retrieved. This single expert expressed the view that the probability estimate should be the same for all options and should be approximately equal to 1 minus the average residual probability that the site is NOT OK for the 34 options.

TABLE 3-12

MAJORITY-REPORT PROBABILITIES OF REPOSITORY CLOSURE

ESF Option	Probabilities Low	Best Judgment	High
1	0.95	0.9951	0.9999
2	0.95	0.9981	0.9999
3	0.95	0.9976	0.9999
4	0.95	0.9986	0.9999
5	0.95	0.9985	0.9999
6	0.95	0.9987	0.9999
7	0.95	0.9978	0.9999
8	0.95	0.9977	0.9999
9	0.95	0.9912	0.9999
10	0.95	0.9959	0.9999
11	0.95	0.9969	0.9999
12	0.95	0.9983	0.9999
13	0.95	0.9988	0.9999
14	0.95	0.9978	0.9999
15	0.95	0.9986	0.9999
16	0.95	0.9987	0.9999
17	0.95	0.9967	0.9999
18	0.95	0.9951	0.9999
19	0.95	0.9973	0.9999
20	0.95	0.9970	0.9999
21	0.95	0.9977	0.9999
22	0.95	0.9970	0.9999
23	0.95	0.9981	0.9999
24	0.95	0.9968	0.9999
25	0.95	0.9973	0.9999
26	0.95	0.9913	0.9999
27	0.95	0.9958	0.9999
28	0.95	0.9966	0.9999
29	0.95	0.9973	0.9999
30	0.95	0.9985	0.9999
31	0.95	0.9965	0.9999
32	0.95	0.9981	0.9999
33	0.95	0.9978	0.9999
34	0.95	0.9947	0.9999

The likelihood of waste retrieval is influenced principally by a factor described as "insufficient technical confidence," as shown in Appendix B, Figure B-11. This factor is influenced, in turn, principally by

- Consequence estimates for postclosure releases of radionuclides, as influenced by the prior release estimates and by the extent to which the site is explored during preclosure; and

- Residual uncertainty estimates, as influenced by the residual probability that the site is NOT OK, given that the outcome of early and late testing indicates that it is OK, and by the extent to which the site is explored during preclosure.

In addition, as indicated in the influence diagram, the panelists felt that the likelihood of regulatory approval of construction and operation might be influential in assessing the likelihood of waste retrieval.

The seven options with probabilities of waste retrieval in the high range of 99.85 percent to 99.88 percent are 4, 5, 6, 13, 15, 16, and 30. None of these options ranks less than fourth on residual probability that the site is NOT OK, less than fourteenth on regulatory approval, or less than second on radionuclide releases. Apart from Option 30, this group of options places primary emphasis on early testing of the TS unit and features (1) shafts constructed by the drill-and-blast method, in conjunction with a ramp, or (2) two access ramps. Option 15 ranks third against repository closure and first against the other three factors. Option 16 ranks second against waste retrieval and the residual probability that the site is NOT OK, first against releases, and seventh against repository approval. Options 15 and 16 have three offset emplacement areas on two levels. Options 9 and 26 were ranked lowest on all four factors. These options feature a shaft that is constructed by the blind-boring method. Options 1 and 18 have two "small" access shafts and no access ramps, and are ranked low on all four measures.

In summary, the factors that favorably influenced the likelihood of repository closure were those discussed in Section 3.2.3 as being important to achieving a high probability of regulatory approval. These factors related to an ESF testing strategy and design features that promote enhanced testing accuracy, and to a repository design that enhanced the potential for increasing the radionuclide travel time from the waste to the water table.

3.2.5 Programmatic Viability

The estimates for the probability of near-term success in maintaining program viability for the 34 options are presented in Table 3-13. These estimates represent the majority report by the Expert Panel on Programmatic Viability. The best-judgment probabilities range from a high of 0.90 to a low of 0.45. The low-probability estimate ranged by an order of magnitude from 0.50 to 0.05, and the high-probability estimate ranged from 0.99 to 0.90. A minority report, provided by one member of the panel, is shown in Table 3-14. The minority report was much more optimistic, with best-judgment probabilities that ranged from 1.0 to 0.8 and low probabilities that ranged from 1.0 to 0.7. This single expert judged a high probability of 1.0 for all options, indicating insensitivity to the variations in features between and among options illustrated in Figures 3-3 and 3-4.

The influence diagram for programmatic viability was discussed in Section 3.1.1, along with the identification of those factors considered significant for discriminating between and among options. Key factors influencing programmatic viability included resolution of NWTRB and NRC concerns and the end-date for late testing. Discussions among panel members suggested that ESF costs and redesign complications apparently had little if any influence on the collective judgment of the majority, nor on the judgment of the minority panel members.

The resolution of NWTRB recommendations deal with (1) use of mechanical mining techniques, (2) exploration of the Ghost Dance Fault at more than one location, (3) east-west exploratory drift in the TS unit, (4) ramp access into the east side of the repository block, and (5) exploration of the softer tuff units above and below the TS unit. The resolution of NRC objections and comments concern (1) incompatibility of tests with construction operations, (2) inadequate MTL area, (3) extended test durations, (4) exploratory drifting to investigate potentially adverse conditions, (5) differentiation between blast-induced and natural fractures, and (6) an in-situ waste package test.

The features of the highest-ranked options would tend to resolve many of the concerns expressed by the NWTRB and the NRC. With the exception of Option 1, all of the options feature an enlarged MTL area and exploration of the Ghost Dance Fault in more than one location. In the group of 17 highest-ranked options from the majority

TABLE 3-13

MAJORITY-REPORT PROBABILITIES FOR NEAR-TERM SUCCESS IN MAINTAINING PROGRAMMATIC VIABILITY

ESF Option	Probabilities Low	Best Judgment	High
1	0.10	0.55	0.90
2	0.20	0.73	0.95
3	0.10	0.52	0.90
4	0.20	0.74	0.95
5	0.10	0.58	0.90
6	0.30	0.78	0.95
7	0.40	0.79	0.99
8	0.10	0.64	0.90
9	0.05	0.45	0.90
10	0.10	0.58	0.90
11	0.10	0.56	0.90
12	0.10	0.58	0.90
13	0.40	0.81	0.95
14	0.10	0.51	0.90
15	0.10	0.54	0.90
16	0.05	0.53	0.90
17	0.10	0.56	0.90
18	0.10	0.52	0.90
19	0.20	0.77	0.99
20	0.10	0.67	0.95
21	0.25	0.77	0.99
22	0.30	0.77	0.95
23	0.50	0.87	0.99
24	0.50	0.90	0.99
25	0.40	0.84	0.99
26	0.05	0.55	0.90
27	0.40	0.83	0.95
28	0.40	0.79	0.99
29	0.30	0.73	0.95
30	0.40	0.89	0.99
31	0.10	0.70	0.95
32	0.10	0.62	0.90
33	0.10	0.59	0.90
34	0.10	0.53	0.90

TABLE 3-14

MINORITY-REPORT (1 EXPERT) PROBABILITIES FOR NEAR-TERM SUCCESS IN MAINTAINING PROGRAMMATIC VIABILITY

ESF Option	Probabilities: Low	Best Judgment	High
1	0.70	0.85	1.00
2	0.90	0.95	1.00
3	0.80	0.90	1.00
4	1.00	1.00	1.00
5	1.00	1.00	1.00
6	0.90	0.95	1.00
7	0.90	0.95	1.00
8	0.80	0.90	1.00
9	0.90	0.95	1.00
10	0.80	0.90	1.00
11	0.80	0.90	1.00
12	1.00	1.00	1.00
13	1.00	1.00	1.00
14	1.00	1.00	1.00
15	0.70	0.85	1.00
16	0.70	0.85	1.00
17	0.80	0.90	1.00
18	0.80	0.90	1.00
19	1.00	1.00	1.00
20	0.90	0.95	1.00
21	1.00	1.00	1.00
22	1.00	1.00	1.00
23	1.00	1.00	1.00
24	1.00	1.00	1.00
25	0.90	0.95	1.00
26	0.60	0.80	1.00
27	0.50	0.80	1.00
28	0.90	0.95	1.00
29	1.00	1.00	1.00
30	0.70	0.85	1.00
31	1.00	1.00	1.00
32	0.70	0.85	1.00
33	0.70	0.85	1.00
34	0.70	0.80	1.00

report, 12 options (approximately 70 percent) place primary emphasis on early testing of the CH unit. In particular, Options 23, 24, 25, 27, and 30, which are the five highest-ranked options with respect to programmatic viability, are designed specifically for early access to, and testing in, the CH unit. These options, along with Options 7 and 13, feature at least one access ramp on the east side of the repository block that intersects the Drill-Hole Wash structure at the north end, and the use of mechanical-mining methods for all shaft, ramp, and MTL (except Option 23) construction. Options 13 and 30 have the MTL situated in the extreme southeast corner of the repository block, and access ramps into the east side of the repository block at the south end of the block. Pertaining to the discriminating factor defined as the end-date of late testing, Options 13, 23, 24, and 30 are projected to be in the late Year 2000 to early Year 2001 time frame, which would be about 12 to 18 months earlier than for many of the other options.

The minority report assigned low, best-judgment, and high probability estimates of unity to 12 options, seven of which place primary emphasis on early testing of the CH unit. These seven options were projected to complete characterization testing in mid- to late-2000, while the other five, which place primary emphasis on early testing of the TS unit, were projected to complete testing in mid- to late- 2001. The potential for this suite of options to accommodate the concerns of the NWTRB and the NRC could be judged to range from high to moderate, with the majority being at the moderately high level.

4.0 CONSEQUENCE ESTIMATES

4.1 Process

As discussed in Section 2, the MUA component of the methodology contained nine consequence objectives and associated performance measures that required quantification for each of the 34 options. These are

- Radionuclide releases to the accessible environment during the first 10,000 years after repository closure, expressed as a fraction of the EPA release limits (40 CFR Part 191 [EPA, 1987]);

- Radiological exposures of repository workers before repository closure, expressed as person-rems of radiation exposure;

- Radiological exposures of members of the public before repository closure, expressed as person-rems of radiation exposure;

- Nonradiological safety effects to repository workers during preclosure, expressed as fatalities due to accidents;

- Degradation of aesthetic properties during preclosure, expressed in terms of visual impacts according to a constructed scale;

- Degradation of historical properties during preclosure, expressed as hectares of disturbed area containing historical properties;

- Direct cost of the ESF and the associated repository, expressed as annualized dollars discounted to 1989;

- Indirect costs of the OCRWM program, including the repository, expressed as annualized dollars discounted to 1989; and

- Benefit that results from a closed, functioning repository, expressed in terms of 1989 dollars.

Apart from the benefit that would result from a closed, functioning repository, consequence estimates were provided either directly or indirectly, and as appropriate, by Expert Panels on Postclosure Health, Preclosure Radiological Health, Preclosure Nonradiological Safety, Aesthetic Properties, Historical Properties, and Cost and Schedule. All of the scoring sessions in which the consequence estimates were determined, as well as those sessions in which influence diagrams were developed, were facilitated by the Decision Methodology Group and formally recorded by a court reporter with attendant notes prepared by a member of the Decision Methodology Group (see Appendices B.1.9 through B.1.16, B.2.9 through B.2.15, and D.4 through D.11). In addition, technical support was provided during the sessions, as appropriate, by representatives of the Sandia Management Lead Group and the Design and Testing Support Groups.

4.1.1 Influence Diagrams and Performance Measure Scales

Prior to obtaining quantitative estimates of the expected consequences for each of the 34 options, influence diagrams were developed for each performance measure except for the benefit of a closed repository (see Appendix B). As explained in Section 3.1.1, an influence diagram is a logically ordered assemblage of factors that influence achieving some level of performance against an objective. In particular, the factors at the lowest level in a diagram could be identified with specific features of an option.

For example, the influence diagram for aesthetic impacts to the environment was developed by the Expert Panel on Aesthetic Properties and is shown in Figure 4-1. At the upper level of the diagram, the significance of the aesthetic impact is influenced by (1) visibility of the impact to people, or populations, and (2) the magnitude and location of the impact in the sense of contrasting form, color, and lighting. Visibility is influenced principally by the location of the impact relative to vantage points on the ground from which the impact could be seen by the human eye. With respect to the Yucca Mountain site and the 34 options, the key vantage points are located on U.S. Route 95, a highway located south of the site, and any associated rest stops along the highway. The magnitude and location of a visual impact are influenced principally by the location of observable roadcuts and traffic in and around the ESF surface facilities, and by the location of skyline structures, such as shaft head frames and microwave towers. Thus, the principal features that must be identified and located for the purpose of scoring an option on the basis of aesthetic impacts are vantage points, roadcuts,

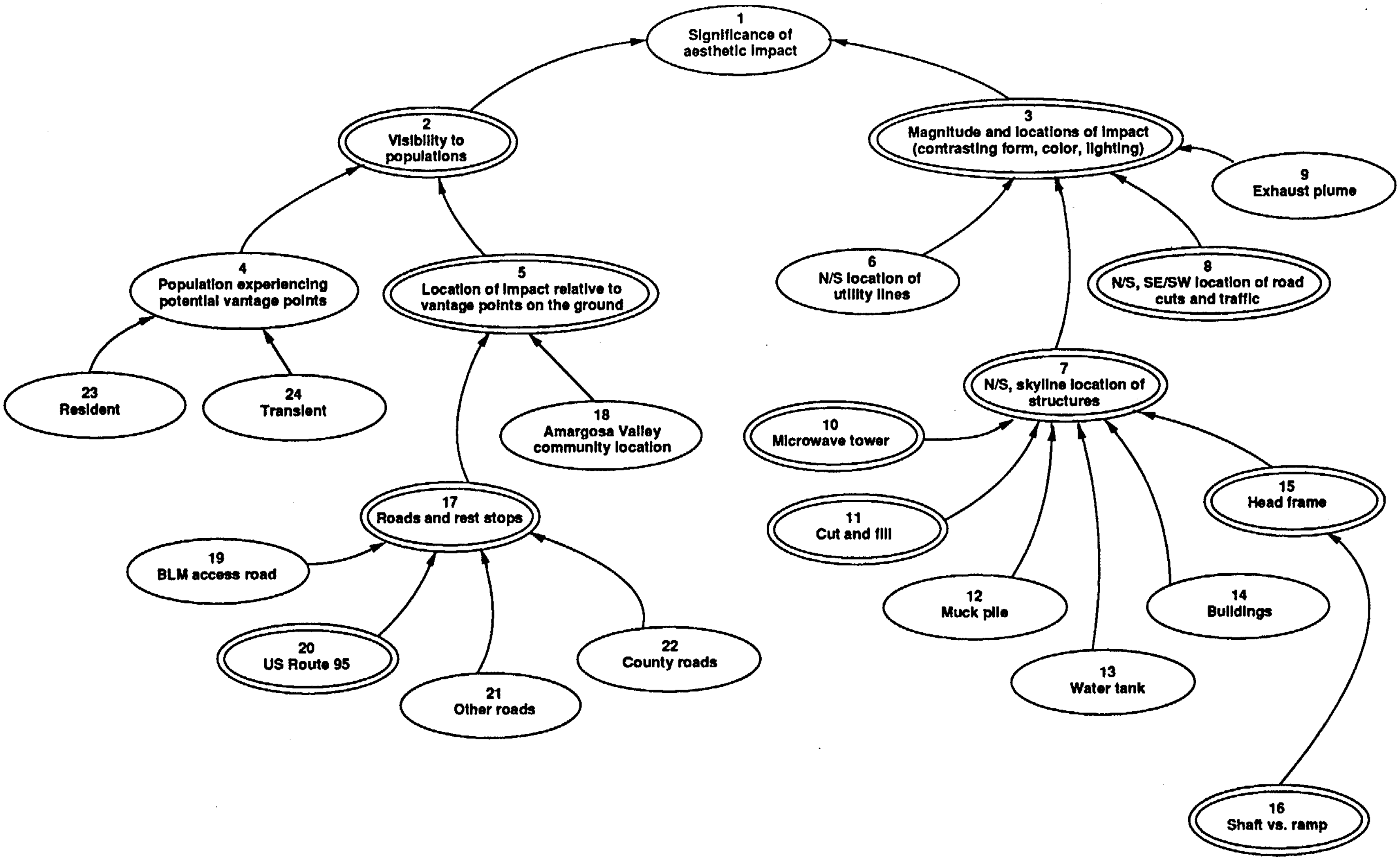

Figure 4-1. Factors That Influence the Aesthetic Impact of the ESF-Repository

traffic, and skyline structures. These factors were highlighted with double-bubbles in the influence diagram to indicate their significance for discriminating between and among options.

Apart from aesthetic impacts, all of the performance measures could be quantified in terms of radionuclide releases, person-rems of radiation dose, fatalities, hectares of disturbance, or discounted dollars. The measurement scale for such basic measures is known as a natural scale. For aesthetic impacts, a constructed scale was developed by the Expert Panel on Aesthetic Properties. This constructed scale, shown in Table 2-3, consists of 13 levels of visual impact that are expressed in terms of major (skyline structures), moderate (structures and facilities), and minor (roadcuts and traffic) impacts in combination with a single vantage point or multiple vantage points. The principal factors used in the qualitative descriptions of the levels of visual impact are those determined to be key factors in the influence diagram for discriminating between and among options.

4.1.2 Stages of the Scoring Process

The process of scoring the 34 options against the performance measures to obtain consequence estimates was similar in most respects to that described in Sections 3.1.3 through 3.1.7 for probability encoding. The sequence of formally structured stages are discussed in detail in Stael von Holstein and Matheson (1979) and Merkhofer (1987a) and include (1) motivating the members of the particular expert panel; (2) structuring the performance measure to be estimated; (3) conditioning the panel members for the estimating task; (4) actually estimating the consequences; (5) resolving differences among the panel members and aggregating estimates to form a possible basis for consensus; and (6) generating a set of consensus estimates and verifying that the selected estimates represent the panel's recommendation for use in the comparative evaluation of the 34 options.

The principal exception to the process described above occurred with the quantification of the direct costs and the associated indirect program costs. Direct costs were developed by construction-cost estimators in conjunction with the Design Support Group. The Expert Panel on Cost and Schedule was convened in a formal session for the purpose of judging the validity of the basis on which the direct costs were estimated. The indirect cost estimates were prepared by representatives of Roy F. Weston, Inc., acting on behalf of DOE-Headquarters (HQ), in conjunction with representatives of SNL. These costs were based on life-cycle costs for the repository system that were developed by DOE-HQ in 1989.

4.2 Presentation and Discussion of Results

The scoring process involved obtaining eight sets of high, best-judgment, and low consequence estimates from five expert panels and two groups of cost estimators. The expert panels gave estimates for postclosure health, preclosure radiologic health (both of repository workers and members of the public), preclosure nonradiological safety, aesthetic impacts, and historical property impacts. The cost estimators provided estimates for direct costs and indirect program costs. All estimates represented consensus estimates because there were no minority reports.

4.2.1 Postclosure Health Impacts

The low, best-judgment, high, and maximum estimates of radionuclide releases from the waste-emplacement area to the accessible environment during the first 10,000 years after closure for the 34 options are given in Table 4-1. The estimates for releases were obtained from the Expert Panel on Postclosure Health by means of a formal scoring process. Separate estimates were obtained for releases by aqueous transport alone and for releases by aqueous transport plus gaseous transport. The panel estimated releases at four different confidence levels: 5 percent, 50 percent, 95 percent, and 99.9 percent, corresponding to low, best-judgment, high, and maximum, respectively. It was the consensus judgment of the expert panel that the release estimates for Options 18 through 34 were identical to those for Options 1 through 17.

The release estimates for aqueous transport were extremely small, ranging from a low best-judgment of 2.3×10^{-7} of the EPA release limits to a high best-judgment of 5.1×10^{-6}. Apart from the high estimates of 0.02 for Option Pair 9 and 26, the low, high, and maximum release estimates are uniformly 10^{-12}, 0.01, and 1 times the EPA release limits, respectively, and are insensitive to the variations in design features between and among options.

The best-judgment estimates of releases by aqueous/gaseous transport range from 0.017 to 0.023 of the EPA release limits. The low, high, and maximum estimates are 10^{-5}, 0.2, and 2 times the EPA release limit, respectively.

TABLE 4-1

RADIONUCLIDE RELEASES TO THE ACCESSIBLE ENVIRONMENT DURING POSTCLOSURE

Units: fraction of EPA release limit

	Aqueous Transport				Gaseous and Aqueous Transport			
Option	Low	Best Judgment	High	Max	Low	Best Judgment	High	Max
1	10^{-12}	1.0×10^{-6}	0.01	1	10^{-5}	0.020	0.2	2
2	10^{-12}	6.7×10^{-7}	0.01	1	10^{-5}	0.019	0.2	2
3	10^{-12}	6.3×10^{-7}	0.01	1	10^{-5}	0.020	0.2	2
4	10^{-12}	2.0×10^{-6}	0.01	1	10^{-5}	0.019	0.2	2
5	10^{-12}	7.9×10^{-7}	0.01	1	10^{-5}	0.017	0.2	2
6	10^{-12}	5.5×10^{-7}	0.01	1	10^{-5}	0.017	0.2	2
7	10^{-12}	8.1×10^{-7}	0.01	1	10^{-5}	0.020	0.2	2
8	10^{-12}	9.4×10^{-7}	0.01	1	10^{-5}	0.020	0.2	2
9	10^{-12}	5.1×10^{-6}	0.02	1	10^{-5}	0.023	0.2	2
10	10^{-12}	9.4×10^{-7}	0.01	1	10^{-5}	0.020	0.2	2
11	10^{-12}	8.1×10^{-7}	0.01	1	10^{-5}	0.020	0.2	2
12	10^{-12}	8.5×10^{-7}	0.01	1	10^{-5}	0.017	0.2	2
13	10^{-12}	6.4×10^{-7}	0.01	1	10^{-5}	0.017	0.2	2
14	10^{-12}	2.2×10^{-6}	0.01	1	10^{-5}	0.017	0.2	2
15	10^{-12}	3.1×10^{-7}	0.01	1	10^{-5}	0.017	0.2	2
16	10^{-12}	2.3×10^{-7}	0.01	1	10^{-5}	0.017	0.2	2
17	10^{-12}	2.3×10^{-6}	0.01	1	10^{-5}	0.020	0.2	2
18	10^{-12}	1.0×10^{-6}	0.01	1	10^{-5}	0.020	0.2	2
19	10^{-12}	6.7×10^{-7}	0.01	1	10^{-5}	0.019	0.2	2
20	10^{-12}	6.3×10^{-7}	0.01	1	10^{-5}	0.020	0.2	2
21	10^{-12}	2.0×10^{-6}	0.01	1	10^{-5}	0.019	0.2	2
22	10^{-12}	7.9×10^{-7}	0.01	1	10^{-5}	0.017	0.2	2
23	10^{-12}	5.5×10^{-7}	0.01	1	10^{-5}	0.017	0.2	2
24	10^{-12}	8.1×10^{-7}	0.01	1	10^{-5}	0.020	0.2	2
25	10^{-12}	9.4×10^{-7}	0.01	1	10^{-5}	0.020	0.2	2
26	10^{-12}	5.1×10^{-6}	0.02	1	10^{-5}	0.023	0.2	2
27	10^{-12}	9.4×10^{-7}	0.01	1	10^{-5}	0.020	0.2	2
28	10^{-12}	8.1×10^{-7}	0.01	1	10^{-5}	0.020	0.2	2
29	10^{-12}	8.5×10^{-7}	0.01	1	10^{-5}	0.017	0.2	2
30	10^{-12}	6.4×10^{-7}	0.01	1	10^{-5}	0.017	0.2	2
31	10^{-12}	2.2×10^{-6}	0.01	1	10^{-5}	0.017	0.2	2
32	10^{-12}	3.1×10^{-7}	0.01	1	10^{-5}	0.017	0.2	2
33	10^{-12}	2.3×10^{-7}	0.01	1	10^{-5}	0.017	0.2	2
34	10^{-12}	2.3×10^{-6}	0.01	1	10^{-5}	0.020	0.2	2

The principal factors that influence releases from the repository to the accessible environment were discussed in some detail in Section 3.2.2. Option Pairs 16 and 33 and Option Pairs 15 and 32 were ranked first and second, respectively, on releases by aqueous transport, and in the group of highest-ranked options for releases by aqueous/gaseous transport (a high ranking implies comparatively lower releases). These four options feature three offset emplacement areas on two levels, with the nominal distance from the emplacement area to the water table being greater than for any of the other 30 options. Option Pairs 5 and 22, 6 and 23, 12 and 29, 13 and 30, and 14 and 31 are included in the group of highest-ranked options for releases by aqueous/gaseous transport. These options feature access by two ramps (Option Pairs 6 and 23 and 13 and 30), or by the combination of a shaft and ramp on the south end of the repository block (Option Pairs 5 and 22, 12 and 29, and 14 and 31). For releases by aqueous transport and by aqueous/gaseous transport, Option Pair 9 and 26 ranked last. These options feature shaft construction by the blind-boring technique.

4.2.2 Preclosure Radiological Releases

The consequence estimates for radiological exposure, expressed as person-rems, to repository workers and members of the public before repository closure are given in Tables 4-2 and 4-3, respectively. The estimates for Options 1 through 17 were obtained from the Expert Panel on Preclosure Radiological Health Effects by means of a formal scoring process. It was the consensus opinion of the members of the expert panel that the consequence estimates for Options 18 through 34 were identical to those for Options 1 through 17.

The expert panel estimated releases at three confidence intervals: 5 percent, 50 percent, and 95 percent, representing the low, best-judgment, and high estimates, respectively. For repository workers, the best-judgment estimates of radiation exposure ranged over an order of magnitude, from a low of 0.01 person-rems to a high of 0.2 person-rems, with an average of about 0.09 person-rems. The low estimate was judged to be insensitive to variations in design features between and among options. The high estimate of radiation exposure ranged between 2 and 40 person-rems. For members of the public, the levels of radiation exposure were judged to be very small, ranging from $2x10^{-7}$ to $2x10^{6}$ person-rems for the best-judgement estimate and from 10^{-4} to $2x10^{-4}$ person-rems for the high estimate. The low estimate was judged to be uniformly 10^{-9} person-rems for all ESF options.

TABLE 4-2

PRECLOSURE RADIOLOGICAL RELEASES TO REPOSITORY WORKERS

Units: person-rems

ESF Option	Low	Best Judgment	High
1	10^{-5}	0.05	10
2	10^{-5}	0.05	10
3	10^{-5}	0.05	10
4	10^{-5}	0.05	10
5	10^{-5}	0.10	20
6	10^{-5}	0.05	10
7	10^{-5}	0.10	20
8	10^{-5}	0.10	20
9	10^{-5}	0.10	20
10	10^{-5}	0.10	20
11	10^{-5}	0.10	20
12	10^{-5}	0.20	40
13	10^{-5}	0.20	40
14	10^{-5}	0.20	40
15	10^{-5}	0.01	2
16	10^{-5}	0.01	2
17	10^{-5}	0.10	20
18	10^{-5}	0.05	10
19	10^{-5}	0.05	10
20	10^{-5}	0.05	10
21	10^{-5}	0.05	10
22	10^{-5}	0.10	20
23	10^{-5}	0.05	10
24	10^{-5}	0.10	20
25	10^{-5}	0.10	20
26	10^{-5}	0.10	20
27	10^{-5}	0.10	20
28	10^{-5}	0.10	20
29	10^{-5}	0.20	40
30	10^{-5}	0.20	40
31	10^{-5}	0.20	40
32	10^{-5}	0.01	2
33	10^{-5}	0.01	2
34	10^{-5}	0.10	20

TABLE 4-3

PRECLOSURE RADIOLOGICAL RELEASES TO MEMBERS OF THE PUBLIC

Units: person-rems

ESF Option	Low	Best Judgment	High
1	10^{-9}	$1x10^{-6}$	0.0001
2	10^{-9}	$1x10^{-6}$	0.0001
3	10^{-9}	$1x10^{-6}$	0.0001
4	10^{-9}	$1x10^{-6}$	0.0001
5	10^{-9}	$2x10^{-6}$	0.0002
6	10^{-9}	$1x10^{-6}$	0.0001
7	10^{-9}	$1x10^{-6}$	0.0001
8	10^{-9}	$1x10^{-6}$	0.0001
9	10^{-9}	$1x10^{-6}$	0.0001
10	10^{-9}	$1x10^{-6}$	0.0001
11	10^{-9}	$1x10^{-6}$	0.0001
12	10^{-9}	$2x10^{-6}$	0.0001
13	10^{-9}	$2x10^{-6}$	0.0001
14	10^{-9}	$2x10^{-6}$	0.0001
15	10^{-9}	$2x10^{-7}$	0.0001
16	10^{-9}	$2x10^{-7}$	0.0001
17	10^{-9}	$1x10^{-6}$	0.0001
18	10^{-9}	$1x10^{-6}$	0.0001
19	10^{-9}	$1x10^{-6}$	0.0001
20	10^{-9}	$1x10^{-6}$	0.0001
21	10^{-9}	$1x10^{-6}$	0.0001
22	10^{-9}	$2x10^{-6}$	0.0002
23	10^{-9}	$1x10^{-6}$	0.0001
24	10^{-9}	$1x10^{-6}$	0.0001
25	10^{-9}	$1x10^{-6}$	0.0001
26	10^{-9}	$1x10^{-6}$	0.0001
27	10^{-9}	$1x10^{-6}$	0.0001
28	10^{-9}	$1x10^{-6}$	0.0001
29	10^{-9}	$2x10^{-6}$	0.0001
30	10^{-9}	$2x10^{-6}$	0.0001
31	10^{-9}	$2x10^{-6}$	0.0001
32	10^{-9}	$2x10^{-7}$	0.0001
33	10^{-9}	$2x10^{-7}$	0.0001
34	10^{-9}	$1x10^{-6}$	0.0001

The factors that influence radiological health effects to repository workers are essentially identical to those that influence radiological health effects to members of the public, as shown by Appendix B, Figures B-14 and B-15. It was the consensus judgment of the expert panel that routine surface and underground operations provided no substantive basis for discriminating between and among options. Furthermore, in their view, the only accident of significance for purposes of discrimination would involve the vehicle or vehicles transporting the radioactive waste from the surface to the underground emplacement areas. The accident scenario would require that a transporter runaway be initiated in the access ramp and, subsequently, the transporter would collide with the wall of the ramp, or with the wall of the main access drift in the emplacement area, or with another transporter in the emplacement area. The collision would rupture the containment structure of the transporter cask and result in a release of radionuclides. The frequency of runaway accidents is influenced principally by the complexity of the layout of access drifts and disposal rooms and by the length and inclination of the main access drift.

Option Pairs 15 and 32 and 16 and 33 were judged to have the least potential for a transporter runaway accident, and correspondingly, the lowest level of radiological releases to the repository workers and to members of the public. These options feature three offset emplacement areas on two levels of the facility, with the main access drifts having relatively little inclination. Option Pairs 12 and 29, 13 and 30, and 14 and 31 were judged to have the potential for the highest releases.

4.2.3 Preclosure Nonradiological Safety

The consequence estimates for fatalities among repository workers due to nonradiological accidents are given in Table 4-4 for Scenarios A, B, C and D, and E of the decision tree. (The scenarios are identified in Figure 2-1 and described in the associated text.) To obtain these estimates, the Expert Panel on Preclosure Nonradiological Safety first established the accident fatality rates on the basis of statistical data from the mining industry and the Nevada Test Site, and, second, estimated the expected numbers of fatalities under the various scenarios for Options 1 through 17. As shown in the influence diagram in Appendix B, Figure B-16, the estimated fatality rates depend principally on the method used for constructing the access drifts and emplacement rooms: i.e., mechanical mining with tunnel-boring machines or drill-and-blast mining. The number of expected fatalities is the product of

TABLE 4-4

PRECLOSURE NONRADIOLOGICAL FATALITIES AMONG REPOSITORY WORKERS

Units: fatalities

	Scenario E			Scenario C, D			Scenario B			Scenario A		
Option	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low
1	0.8	0.7	0.6	1.2	1.0	0.9	26.1	16.8	13.2	20.7	13.2	10.3
2	1.1	0.9	0.9	1.4	1.2	1.1	27.5	17.5	13.5	22.1	13.9	10.6
3	1.1	0.9	0.8	1.3	1.0	1.0	27.6	17.6	13.5	22.1	13.9	10.6
4	1.3	1.1	1.0	1.6	1.3	1.3	27.7	17.6	13.6	22.2	14.0	10.7
5	1.3	1.0	1.0	1.6	1.3	1.3	26.9	17.1	13.2	21.5	13.6	10.4
6	1.2	1.0	1.0	1.6	1.3	1.2	27.0	17.2	13.2	22.0	13.9	10.6
7	1.1	0.9	0.8	1.4	1.1	1.1	23.9	15.4	12.4	20.0	12.6	10.2
8	1.2	1.0	1.0	1.4	1.1	1.1	23.9	15.4	12.4	20.0	12.6	10.2
9	1.1	0.9	0.9	1.4	1.1	1.1	23.9	15.4	12.4	20.0	12.6	10.2
10	1.1	0.9	0.9	1.4	1.1	1.1	23.9	15.4	12.4	20.0	12.6	10.2
11	1.1	0.9	0.9	1.4	1.2	1.1	23.9	15.4	12.5	20.1	12.6	10.2
12	1.2	1.0	0.9	1.4	1.2	1.1	24.4	15.5	12.3	20.5	12.7	10.2
13	1.3	1.1	1.0	1.5	1.3	1.2	24.1	15.3	12.1	20.2	12.6	10.0
14	1.2	1.0	1.0	1.4	1.2	1.1	23.8	15.1	12.0	19.9	12.3	9.8
15	1.1	0.9	0.9	1.5	1.2	1.2	26.1	16.9	13.8	22.6	14.1	11.5
16	1.1	0.9	0.9	1.4	1.2	1.1	26.8	17.3	14.2	23.5	14.7	11.9
17	1.0	0.9	0.8	1.4	1.2	1.1	24.4	15.5	12.3	20.4	12.7	10.1
18	0.6	0.5	0.5	1.1	0.9	0.9	26.0	16.8	13.2	20.7	13.2	10.3
19	1.1	0.9	0.9	1.4	1.2	1.1	27.5	17.5	13.4	22.1	13.9	10.6
20	0.7	0.6	0.6	1.2	1.0	1.0	27.6	17.5	13.4	22.1	13.9	10.6
21	1.2	1.0	0.9	1.6	1.3	1.3	27.6	17.6	13.5	22.2	14.0	10.7
22	1.4	1.1	1.1	1.6	1.3	1.3	26.9	17.1	13.2	21.5	13.5	10.4
23	1.2	1.0	0.9	1.5	1.3	1.2	27.0	17.2	13.2	22.0	13.9	10.6
24	1.1	0.9	0.8	1.3	1.1	1.1	23.8	15.3	12.4	20.0	12.6	10.2
25	0.8	0.7	0.6	1.3	1.1	1.1	23.8	15.3	12.4	20.0	12.6	10.2
26	0.9	0.7	0.7	1.3	1.1	1.1	23.8	15.3	12.4	20.0	12.6	10.2
27	0.8	0.7	0.7	1.3	1.1	1.1	23.8	15.3	12.4	20.0	12.6	10.2
28	1.0	0.8	0.8	1.4	1.1	1.1	23.9	15.4	12.4	20.0	12.6	10.2
29	1.1	0.9	0.9	1.4	1.1	1.1	24.4	15.5	12.3	20.5	12.7	10.1
30	1.0	0.8	0.8	1.5	1.3	1.2	24.1	15.3	12.1	20.2	12.5	10.0
31	1.2	1.0	0.9	1.4	1.1	1.1	23.8	15.1	12.0	19.9	12.3	9.8
32	0.9	0.7	0.7	1.5	1.2	1.2	26.1	16.9	13.8	22.6	14.1	11.5
33	1.0	0.9	0.8	1.4	1.2	1.1	26.8	17.3	14.2	23.5	14.7	11.9
34	0.9	0.7	0.7	1.4	1.2	1.1	24.4	15.5	12.3	20.4	12.7	10.1

the expected fatality rate and the number of worker-hours for the specified construction method. The numbers of fatalities given in Table 4-4 were calculated by the Sandia Management Lead Group on the basis of the worker-hour estimates determined by the Design Support Group and the fatality rates established by the expert panel during the formal scoring session.

The expert panel provided estimates for nonradiological fatalities at three confidence intervals: 5 percent, 50 percent, and 95 percent, representing low, best-judgment, and high estimates, respectively. The best-judgment number of fatalities calculated for early testing (Scenario E) was of the order of one, and slightly greater than one during late testing (Scenarios C and D). The panel decided that two fatalities from construction accidents could be expected during the entire process of characterization testing, effectively independent of differences in the construction methods between and among options. For Scenarios A and B, the best-judgment estimates of fatalities among workers ranged from 12 to 15, and from 15 to 18, respectively. Option Pairs 15 and 32 and 16 and 33 ranked lowest, or low, for both of these scenarios; that is, these four options were expected to produce the highest number, or almost the highest number, of fatalities because of construction-associated accidents. These options feature three offset emplacement areas on two levels of the facility and require relatively high numbers of construction worker-hours. On the other hand, Options 14 and 31 were projected to produce the fewest fatalities because of relatively low numbers of construction worker-hours together with the use of relatively safer mechanical mining methods. Options 1 through 6 and 18 through 23, featuring construction of the emplacement areas by the drill-and-blast mining method, were projected to produce higher numbers of fatalities than most of the other options.

4.2.4 Aesthetic Impacts

The consequence estimates for aesthetic impacts during preclosure are given in Table 4-5. The estimates for Options 1 through 17 were obtained from the Expert Panel on Aesthetics by means of a formal scoring process. The panel estimated scores for aesthetic impacts at three confidence levels: 5 percent, 50 percent, and 95 percent, representing low, best-judgment, and high estimates, respectively. Subsequently, the suite of 17 options was enlarged to 34, featuring the early/late testing concept for the TS and CH units. It was the consensus opinion of the members of the expert panel that the consequence estimates for Options 18 through 34 were identical to those for Options 1 through 17.

TABLE 4-5

AESTHETIC IMPACTS DURING PRECLOSURE

Units: constructed scale (0-12)

ESF Option	Low	Best Judgment	High
1	8	8	9
2	8	8	9
3	8	8	9
4	8	8	9
5	0	0.5	1
6	8	8	9
7	8	8	9
8	8	8	9
9	8	8	9
10	8	8	9
11	8	8	9
12	0	0.5	1
13	0.5	1	1
14	0.5	1	1
15	8	8	9
16	0	0.5	1
17	0.5	1	1
18	8	8	9
19	8	8	9
20	8	8	9
21	8	8	9
22	0	0.5	1
23	8	8	9
24	8	8	9
25	8	8	9
26	8	8	9
27	8	8	9
28	8	8	9
29	0	0.5	1
30	0.5	1	1
31	0.5	1	1
32	8	8	9
33	0	0.5	1
34	0.5	1	1

As discussed in Section 4.1.1, the measurement scale for aesthetic impacts is a constructed scale, consisting of 13 levels of visual impact that are expressed in terms of major (skyline structures), moderate (structures and facilities), and/or minor (roadcuts and traffic) impacts in combination with a single vantage point or multiple vantage points. Twenty-two of the 34 options were assigned a relatively high score of 8, which implies moderate impacts visible from one vantage point in concert with minor impacts visible from multiple vantage points. These options feature shaft and/or ramp access facilities that are located in the north end and northeast side of the repository block. Option Pairs 5 and 22, 12 and 29, and 17 and 34 were judged to produce the greatest visual impact and assigned a score of 0.5. These six options feature a shaft and a ramp on the south end and southeast side, respectively, of the repository block. The surface facilities associated with the shaft and ramp would appear as skyline structures that would be visible from a number of vantage points. The remaining Option Pairs 13 and 30, 14 and 31, and 17 and 34 were assigned a score of 1.

4.2.5 Impacts on Historical Properties

The consequence estimates for impacts on historical properties during preclosure are given in Table 4-6 for Scenarios A and B (repository closure and retrieval, respectively) and Scenarios C, D, and E (the repository is not constructed). The panelists declined to provide high and low probability estimates for the 34 options because of their precise knowledge of the location and extent of the historical properties in each option area. The estimates for Options 1 through 17 were obtained from the Expert Panel on Historical Properties by means of a formal scoring process. It was the consensus opinion of the members of the expert panel that the consequence estimates for Options 18 through 34 were identical to those for Options 1 through 17 because the surface disturbance would be the same for both members of each pair of options.

As described in Section 2.4.2, the performance measure is expressed in terms of hectares (ha) of disturbed area, which includes a severity factor for subsurface deposits of historical properties. The best-judgment estimates vary from a low of 0.028 ha to a high in excess of 2.94 ha for Scenarios A and B and a low of 0.027 ha to a high in excess of 2.4 ha for Scenarios C, D, and E. Under Scenarios C, D, and E, Options 14 and 31 were judged to have the largest impact on historical properties. These options feature a shaft and a ramp in the south end of the block. Option Pairs 5 and 22, 12 and 29, 13

TABLE 4-6

IMPACTS ON HISTORICAL PROPERTIES DURING PRECLOSURE

Units: hectares

ESF Option	Best Judgment (Scenario A, B)	Best Judgment (Scenario C, D, E)
1	2.919	0.418
2	2.930	0.391
3	2.930	0.391
4	2.930	0.391
5	0.028	0.024
6	2.930	0.392
7	2.930	0.391
8	2.930	0.391
9	2.930	0.391
10	2.930	0.391
11	2.930	0.391
12	0.028	0.024
13	0.028	0.025
14	2.413	2.412
15	2.944	0.433
16	0.028	0.024
17	0.028	0.027
18	2.919	0.418
19	2.930	0.391
20	2.930	0.391
21	2.930	0.391
22	0.028	0.024
23	2.930	0.392
24	2.930	0.391
25	2.930	0.391
26	2.930	0.391
27	2.930	0.391
28	2.930	0.391
29	0.028	0.024
30	0.028	0.025
31	2.413	2.412
32	2.944	0.433
33	0.028	0.024
34	0.028	0.027

and 30, 16 and 33, and 17 and 34 were judged to have the least impact on historical properties for all scenarios. These options feature two shafts in the north end of the block (17 and 34), or east-to-west ramps on the north and south ends of the block (13 and 30), or a shaft and an east-to-west ramp on the south end of the block (5 and 22, 12 and 29, and 16 and 33). For Scenarios A and B, it was observed that all options with the tuff ramp located in the north end of the block would have the greatest impact on historical properties.

4.2.6 Cost Impacts

Year-by-year estimates of direct ESF-repository costs and indirect program costs were estimated for the 34 options. The direct ESF-repository costs were developed by the Design Support Group, and the bases for estimating the costs were reviewed by the Expert Panel on Cost and Schedule. The indirect program costs were developed by representatives of Roy F. Weston, Inc. Both groups of cost estimators gave cost estimates at three different confidence intervals: 5 percent, 50 percent, and 95 percent, corresponding to low, best-judgment, and high costs, respectively. Tables 4-7 and 4-8 give the total (undiscounted) direct and indirect cost estimates, respectively, expressed in terms of 1989 dollars.

The range of the best-judgment direct ESF-repository costs for the 34 options under Scenario A is slightly in excess of one billion dollars, with a low for Option Pairs 1 and 18 of about $10.3 billion to a high for Option Pair 16 and 33 of about $11.3 billion. The high estimates are generally two to three billion dollars higher than the best-judgment estimates, while the low estimates are less by about one billion dollars. These costs include those attributable to ESF characterization, repository construction and operation, caretaking, and decommissioning and closure (or retrieval).

The range of the best-judgment indirect program costs under Scenario A is one billion dollars, with a low for Option 22 of $14.2 billion and a high for Option 9 of $15.2 billion. The ten options that cost the least placed primary emphasis on early testing of the CH unit together with early exploration of the TS unit. The high estimates are three to four billion dollars higher than the best-judgment estimates, and the low estimates are about three billion dollars lower. These costs include those attributable to development and evaluation (exclusive of ESF-repository costs), waste transportation, benefits, and the MRS.

TABLE 4-7

DIRECT ESF-REPOSITORY COSTS

Units: $ millions

Option	Scenario F High	Scenario F Best	Scenario F Low	Scenario E High	Scenario E Best	Scenario E Low	Scenario D High	Scenario D Best	Scenario D Low	Scenario C High	Scenario C Best	Scenario C Low	Scenario B High	Scenario B Best	Scenario B Low	Scenario A High	Scenario A Best	Scenario A Low
1	153	103	90	424	358	309	550	653	580	598	820	733	15,667	12,537	11,462	12,700	10,260	9,291
2	245	138	120	601	531	458	702	817	717	742	994	875	16,038	12,785	11,610	13,139	10,554	9,475
3	157	106	92	513	469	402	610	711	621	658	889	780	15,964	12,718	11,546	13,057	10,481	9,406
4	322	182	158	691	564	487	796	851	746	833	1,009	888	16,089	12,823	11,646	13,177	10,582	9,502
5	261	137	119	654	603	519	734	849	741	767	1,019	893	15,952	12,710	11,547	13,019	10,453	9,387
6	266	150	130	632	574	496	727	853	748	759	1,013	890	16,033	12,779	11,606	13,142	10,555	9,477
7	306	144	125	709	595	514	791	900	788	819	1,072	940	16,200	12,891	11,676	13,368	10,720	9,606
8	275	135	117	667	618	531	751	941	824	782	1,119	982	16,256	12,937	11,720	13,426	10,768	9,652
9	285	140	121	718	609	523	782	845	735	809	1,004	876	16,155	12,850	11,638	13,309	10,668	9,559
10	275	135	117	601	506	437	710	873	769	742	1,040	917	16,201	12,890	11,677	13,361	10,711	9,599
11	252	142	123	648	564	486	748	877	769	772	1,008	886	16,211	12,896	11,681	13,359	10,710	9,598
12	267	141	122	687	631	541	769	883	764	801	1,051	910	16,216	12,833	11,548	13,387	10,657	9,465
13	321	151	131	706	658	565	777	873	754	802	1,012	875	16,152	12,783	11,501	13,326	10,609	9,420
14	269	137	118	662	628	538	740	868	750	772	1,033	894	16,126	12,760	11,485	13,284	10,575	9,392
15	299	147	128	664	537	465	786	937	830	812	1,085	963	16,567	13,208	11,991	13,921	11,176	10,042
16	293	144	125	756	726	626	831	988	863	860	1,161	1,018	16,692	13,310	12,084	14,103	11,323	10,175
17	154	103	89	486	438	375	596	699	604	645	874	757	16,123	12,754	11,467	13,279	10,567	9,372
18	166	102	89	413	297	256	560	667	599	593	794	715	15,700	12,567	11,487	12,724	10,281	9,310
19	264	139	121	602	466	400	700	723	633	742	890	782	15,949	12,706	11,537	13,039	10,467	9,394
20	168	103	89	438	315	269	596	655	580	653	837	742	15,908	12,678	11,508	13,009	10,445	9,371
21	338	178	155	680	511	441	795	792	695	831	939	826	16,032	12,776	11,602	13,117	10,532	9,455
22	279	137	119	655	545	468	734	764	665	764	907	794	15,865	12,639	11,478	12,924	10,375	9,312
23	295	155	135	772	528	452	868	802	700	906	967	847	16,005	12,752	11,579	13,086	10,505	9,430
24	324	145	126	745	543	467	821	808	705	852	975	853	16,120	12,820	11,612	13,276	10,640	9,533
25	296	138	119	742	652	557	812	911	790	844	1,088	948	16,222	12,904	11,689	13,383	10,728	9,616
26	302	140	122	686	461	396	795	809	712	833	989	872	16,135	12,832	11,625	13,298	10,658	9,553
27	294	137	119	625	454	388	748	855	754	778	1,015	896	16,181	12,873	11,657	13,356	10,708	9,593
28	267	140	122	659	534	460	757	804	701	861	985	855	16,107	12,815	11,605	13,277	10,644	9,535
29	280	138	119	692	587	502	770	796	685	800	937	808	16,098	12,738	11,458	13,287	10,575	9,384
30	342	153	133	849	587	494	968	971	839	996	1,122	972	16,292	12,897	11,598	13,466	10,721	9,514
31	288	137	119	663	547	467	749	806	697	784	973	843	16,055	12,708	11,433	13,220	10,524	9,341
32	325	151	131	772	617	531	872	934	821	898	1,084	956	16,548	13,194	11,979	13,905	11,163	10,029
33	316	147	127	807	701	601	888	955	826	922	1,135	982	16,678	13,293	12,056	14,078	11,299	10,141
34	168	103	89	421	318	270	576	704	619	623	879	771	16,153	12,779	11,491	13,309	10,592	9,396

TABLE 4-8

INDIRECT PROGRAM COSTS

Units: $ millions

Option	Scenario F			Scenario E			Scenario D			Scenario C			Scenario B			Scenario A		
	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low
1	1216	1216	973	3851	3851	3081	6685	6685	5348	7887	7887	6310	18,895	15,116	12,093	18,204	14,563	11,650
2	1208	1208	966	4263	4263	3410	6752	6752	5401	7970	7970	6376	18,958	15,166	12,133	18,291	14,633	11,706
3	1216	1216	973	4397	4397	3517	6685	6685	5348	7887	7887	6310	18,893	15,114	12,092	18,227	14,581	11,665
4	1222	1222	978	4068	4068	3255	7244	7244	5795	8448	8448	6759	19,621	15,697	12,558	18,955	15,164	12,131
5	1216	1216	973	4686	4686	3749	6685	6685	5348	7887	7887	6310	18,895	15,116	12,093	18,204	14,563	11,650
6	1200	1200	960	4459	4459	3568	6828	6828	5462	8053	8053	6442	19,045	15,236	12,189	18,379	14,703	11,763
7	1208	1208	966	4209	4209	3367	6752	6752	5402	7970	7970	6376	18,956	15,165	12,132	18,315	14,652	11,721
8	1173	1173	938	4442	4442	3553	7119	7119	5695	8316	8316	6653	19,280	15,424	12,339	18,640	14,912	11,929
9	1222	1222	978	4491	4491	3593	7244	7244	5795	8448	8448	6759	19,619	16,695	12,556	18,978	15,182	12,146
10	1185	1185	948	4042	4042	3234	6980	6980	5584	8174	8174	6539	19,155	15,324	12,259	18,515	14,812	11,850
11	1194	1194	956	4172	4172	3337	6891	6891	5513	8110	8110	6488	19,102	15,282	12,225	18,462	14,770	11,816
12	1217	1217	974	4623	4623	3698	6712	6712	5370	7919	7919	6335	18,918	15,134	12,108	18,276	14,621	11,697
13	1232	1232	985	4554	4554	3643	6561	6561	5249	7775	7775	6220	18,797	15,038	12,030	18,154	14,523	11,618
14	1217	1217	974	4799	4799	3839	6713	6713	5370	7919	7919	6336	18,921	15,137	12,109	18,254	14,603	11,683
15	1200	1200	960	3863	3863	3090	6866	6866	5492	8081	8081	6464	19,027	15,222	12,177	18,507	14,806	11,844
16	1208	1208	966	4713	4713	3770	6777	6777	5422	7995	7995	6396	18,966	15,173	12,138	18,493	14,794	11,836
17	1216	1216	973	4342	4342	3474	6685	6685	5348	7887	7887	6310	18,893	15,114	12,092	18,227	14,581	11,665
18	1194	1194	956	2921	2921	2337	6848	6848	5479	8067	8067	6453	19,052	15,242	12,193	18,363	14,690	11,752
19	1257	1257	1005	3802	3802	3041	6944	6944	5555	8192	8192	6554	19,341	15,473	12,378	18,673	14,938	11,950
20	1248	1248	998	3033	3033	2426	6452	6452	5161	7645	7645	6116	18,617	14,894	11,915	17,949	14,359	11,487
21	1264	1264	1011	3458	3458	2767	6291	6291	5033	7525	7525	6020	18,448	14,759	11,807	17,780	14,224	11,379
22	1270	1270	1016	4077	4077	3261	6281	6281	5025	7508	7508	6007	18,421	14,737	11,790	17,728	14,182	11,346
23	1257	1257	1005	3167	3167	2534	6944	6944	5555	8192	8192	6554	19,341	15,473	12,378	18,673	14,938	11,950
24	1257	1257	1005	3572	3572	2858	6360	6360	5088	7576	7576	6061	18,569	14,855	11,884	17,925	14,340	11,472
25	1217	1217	974	4066	4066	3253	6712	6712	5370	7919	7919	6335	18,918	15,134	12,108	18,276	14,621	11,697
26	1248	1248	998	3164	3164	2531	6437	6437	5150	7631	7631	6105	18,597	14,878	11,902	17,954	14,363	11,490
27	1200	1200	960	3254	3254	2603	6828	6828	5463	8053	8053	6443	19,044	15,235	12,188	18,402	14,722	11,777
28	1245	1245	996	3865	3865	3092	6470	6470	5176	7669	7669	6135	18,631	14,905	11,924	17,987	14,390	11,512
29	1272	1272	1017	4103	4103	3282	6222	6222	4978	7471	7471	5977	18,388	14,710	11,768	17,742	14,194	11,355
30	1235	1235	988	2942	2942	2354	6531	6531	5225	7740	7740	6192	18,770	15,016	12,013	18,126	14,501	11,601
31	1248	1248	998	4040	4040	3232	6452	6452	5161	7645	7645	6116	18,617	14,894	11,915	17,949	14,359	11,487
32	1232	1232	986	3580	3580	2864	6562	6562	5250	7775	7775	6220	18,791	15,033	12,026	18,269	14,615	11,692
33	1250	1250	1000	4048	4048	3238	6421	6421	5137	7623	7623	6098	18,599	14,879	11,903	18,125	14,500	11,600
34	1182	1182	946	3156	3156	2525	7017	7017	5614	8210	8210	6568	19,185	15,348	12,279	18,521	14,817	11,853

The direct ESF-repository costs and indirect program costs were discounted to reflect the higher value placed on a dollar spent in the near-term future as compared with a dollar spent in the long-term future. Consistent with the opinion of the Management Panel, the assumed discount rate was 10 percent. Discounted direct ESF-repository costs and discounted indirect program costs are given in Tables 4-9 and 4-10, respectively.

4.2.7 Concluding Remarks

Based on the analyses of the consequence estimates in the previous sections, the following features tended to be identified with lower adverse consequences.

- Offset emplacement areas located on two horizontal levels of the facility, with main access drifts having little inclination -- This feature (1) would minimize the potential for transporter runaway accidents during emplacement operations and associated releases of radionuclides to repository workers and members of the public and (2) increase the radionuclide travel time to the water table during postclosure because of greater distance between the waste-emplacement areas and the water table.

- Construction of the waste-emplacement areas by mechanical mining methods -- This feature reduces the projected number of nonradiological fatalities among repository workers because of fewer worker-hours and safer working conditions during construction operations.

- ESF access by ramps only, with both ramps converted to accommodate muck removal and waste transportation during repository construction and operation -- This feature would reduce the estimated releases of radionuclides to the accessible environment during postclosure, principally because of the lack of a shaft connection from the surface to the CH unit.

- Location of the shafts and ramps at the northern end of the repository block -- This feature would minimize aesthetic impacts because the visibility of shaft/ramp surface facilities and associated roadcuts/traffic would be reduced considerably as compared to the southern end of the block.

TABLE 4-9

DISCOUNTED DIRECT ESF-REPOSITORY COSTS (10% DISCOUNT RATE)

Units: millions of discounted $

	Scenario F			Scenario E			Scenario D			Scenario C			Scenario B			Scenario A		
Option	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low
1	153	90	79	424	252	224	550	379	343	598	423	385	1,374	1,100	1,006	1,361	1,099	996
2	245	119	105	601	364	323	702	475	428	742	520	469	1,492	1,190	1,080	1,481	1,189	1,068
3	157	92	81	513	317	279	610	411	368	658	456	410	1,443	1,150	1,044	1,432	1,149	1,031
4	322	156	138	691	402	358	796	521	469	833	561	507	1,583	1,262	1,146	1,571	1,262	1,133
5	261	118	104	654	398	354	734	494	443	767	535	482	1,516	1,208	1,097	1,504	1,208	1,084
6	266	128	113	632	389	347	727	496	446	759	535	484	1,489	1,187	1,078	1,478	1,187	1,066
7	306	124	109	709	406	360	791	524	472	819	567	511	1,560	1,241	1,124	1,547	1,241	1,112
8	275	116	102	667	409	363	751	526	474	782	567	512	1,476	1,175	1,064	1,464	1,174	1,053
9	285	120	106	718	417	368	782	508	454	809	546	491	1,575	1,253	1,135	1,563	1,253	1,122
10	275	116	102	601	347	308	710	497	448	742	535	483	1,475	1,173	1,063	1,463	1,173	1,051
11	252	122	108	648	386	341	748	507	456	772	537	486	1,507	1,199	1,086	1,495	1,198	1,074
12	267	121	106	687	415	367	769	513	456	801	552	492	1,542	1,220	1,098	1,532	1,220	1,083
13	321	129	114	706	440	390	777	525	467	802	561	500	1,594	1,261	1,135	1,584	1,261	1,119
14	269	117	103	662	410	362	740	503	446	772	541	482	1,519	1,202	1,082	1,510	1,202	1,067
15	299	126	111	664	377	336	786	549	498	812	586	533	1,576	1,257	1,141	1,565	1,256	1,129
16	293	124	109	756	469	417	831	564	508	860	606	548	1,608	1,282	1,164	1,597	1,282	1,152
17	154	89	79	486	298	261	596	402	355	645	447	396	1,447	1,145	1,029	1,438	1,145	1,015
18	166	89	78	413	224	196	560	389	355	593	422	387	1,335	1,068	977	1,322	1,068	967
19	264	119	105	602	337	296	700	452	404	742	499	449	1,587	1,264	1,148	1,574	1,264	1,134
20	168	90	79	438	235	205	596	397	358	653	451	407	1,513	1,206	1,094	1,501	1,205	1,081
21	338	152	134	680	378	334	795	508	456	831	549	496	1,672	1,332	1,210	1,659	1,332	1,196
22	279	118	104	655	382	337	734	477	427	764	517	465	1,613	1,285	1,167	1,600	1,284	1,153
23	295	132	117	772	391	343	868	515	461	906	561	505	1,656	1,320	1,198	1,643	1,319	1,184
24	324	124	109	745	391	344	821	509	455	852	554	498	1,666	1,325	1,200	1,653	1,325	1,187
25	296	118	104	742	450	395	812	548	489	844	590	529	1,601	1,273	1,153	1,588	1,273	1,141
26	302	120	106	686	339	299	795	503	453	833	555	499	1,644	1,307	1,185	1,631	1,307	1,171
27	294	117	104	625	329	288	748	509	459	778	550	496	1,531	1,218	1,103	1,518	1,217	1,091
28	267	120	106	659	376	333	757	491	439	861	542	482	1,616	1,286	1,164	1,603	1,285	1,151
29	280	118	104	692	409	360	770	500	442	800	541	480	1,667	1,319	1,187	1,657	1,319	1,170
30	342	131	115	849	433	372	968	613	543	996	654	581	1,718	1,360	1,223	1,708	1,360	1,207
31	288	118	104	663	376	330	749	487	432	784	534	474	1,589	1,257	1,131	1,579	1,257	1,116
32	325	130	115	772	439	387	872	574	518	898	615	557	1,692	1,349	1,225	1,680	1,349	1,212
33	316	126	111	807	482	424	888	590	523	922	635	566	1,754	1,398	1,268	1,741	1,398	1,254
34	168	89	78	421	233	203	576	403	360	623	445	397	1,370	1,084	975	1,362	1,084	961

TABLE 4-10

DISCOUNTED INDIRECT PROGRAM COSTS (10% DISCOUNT RATE)

Units: millions of discounted $

Option	Scenario F			Scenario E			Scenario D			Scenario C			Scenario B			Scenario A		
	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low	High	Best	Low
1	1216	1119	896	3851	2958	2367	6685	4320	3456	7887	4705	3764	6,678	5,343	4,274	6,678	5,343	4,274
2	1208	1112	889	4263	3186	2548	6752	4335	3468	7970	4715	3772	6,674	5,339	4,272	6,674	5,339	4,272
3	1216	1119	896	4397	3266	2613	6685	4320	3456	7887	4705	3764	6,678	5,343	4,274	6,678	5,343	4,274
4	1222	1125	900	4068	3094	2475	7244	4636	3709	8448	5029	4023	7,095	5,676	4,541	7,095	5,676	4,541
5	1216	1119	896	4686	3417	2734	6685	4320	3456	7887	4705	3764	6,678	5,343	4,274	6,678	5,343	4,274
6	1200	1104	883	4459	3289	2631	6828	4350	3480	8053	4726	3780	6,671	5,337	4,269	6,671	5,337	4,269
7	1208	1112	889	4209	3155	2524	6752	4335	3468	7970	4715	3772	6,675	5,340	4,272	6,675	5,340	4,272
8	1173	1079	863	4442	3261	2609	7119	4415	3532	8316	4752	3802	6,632	5,306	4,244	6,632	5,305	4,244
9	1222	1125	900	4491	3333	2666	7244	4636	3709	8448	5029	4023	7,095	5,676	4,541	7,095	5,676	4,541
10	1185	1090	872	4042	3049	2439	6980	4385	3508	8174	4736	3788	6,634	5,307	4,246	6,634	5,307	4,246
11	1194	1099	879	4172	3127	2501	6891	4365	3492	8110	4734	3787	6,647	5,318	4,254	6,647	5,318	4,254
12	1217	1120	896	4623	3385	2708	6712	4330	3464	7919	4712	3770	6,682	5,346	4,277	6,682	5,346	4,276
13	1232	1134	907	4554	3361	2688	6561	4292	3433	7775	4697	3757	6,697	5,357	4,286	6,697	5,357	4,286
14	1217	1120	896	4799	3475	2780	6713	4330	3464	7919	4712	3770	6,682	5,346	4,277	6,682	5,346	4,277
15	1200	1104	883	3863	2956	2364	6866	4364	3491	8081	4733	3786	6,670	5,336	4,269	6,670	5,336	4,269
16	1208	1111	889	4713	3424	2739	6777	4342	3474	7995	4720	3776	6,674	5,339	4,271	6,674	5,339	4,271
17	1216	1119	896	4342	3235	2588	6685	4320	3456	7887	4705	3764	6,678	5,343	4,274	6,678	5,343	4,274
18	1194	1099	879	2921	2370	1896	6848	4342	3473	8067	4710	3768	6,618	5,294	4,235	6,618	5,294	4,235
19	1257	1157	925	3802	2951	2361	6944	4557	3646	8192	5002	4002	7,134	5,707	4,566	7,134	5,707	4,566
20	1248	1149	919	3033	2462	1970	6452	4268	3414	7645	4679	3743	6,711	5,369	4,295	6,711	5,369	4,295
21	1264	1164	931	3458	2738	2190	6291	4217	3374	7525	4665	3732	6,727	5,382	4,306	6,727	5,382	4,305
22	1270	1169	935	4077	3115	2492	6281	4214	3371	7508	4659	3727	6,718	5,374	4,299	6,718	5,374	4,299
23	1257	1157	925	3167	2557	2046	6944	4557	3646	8192	5002	4002	7,134	5,707	4,566	7,134	5,707	4,566
24	1257	1157	925	3572	2805	2244	6360	4239	3391	7576	4671	3737	6,720	5,376	4,301	6,720	5,376	4,301
25	1217	1120	896	4066	3080	2464	6712	4330	3464	7919	4712	3770	6,682	5,346	4,277	6,682	5,346	4,276
26	1248	1149	919	3164	2548	2038	6437	4262	3410	7631	4673	3738	6,704	5,363	4,290	6,704	5,363	4,290
27	1200	1104	883	3254	2583	2066	6828	4350	3480	8053	4726	3781	6,671	5,337	4,270	6,671	5,337	4,270
28	1245	1146	917	3865	2982	2386	6470	4271	3417	7669	4682	3745	6,709	5,367	4,294	6,709	5,367	4,293
29	1272	1171	937	4103	3132	2505	6222	4196	3357	7471	4656	3725	6,730	5,384	4,307	6,730	5,384	4,307
30	1235	1137	909	2942	2396	1917	6531	4283	3426	7740	4689	3751	6,694	5,355	4,284	6,694	5,355	4,284
31	1248	1149	919	4040	3082	2466	6452	4268	3414	7645	4679	3743	6,711	5,369	4,295	6,711	5,369	4,295
32	1232	1134	907	3580	2799	2240	6562	4292	3434	7775	4697	3758	6,698	5,358	4,287	6,698	5,358	4,286
33	1250	1151	921	4048	3088	2471	6421	4258	3406	7623	4676	3741	6,715	5,372	4,298	6,715	5,372	4,298
34	1182	1088	870	3156	2515	2012	7017	4394	3516	8210	4741	3793	6,636	5,309	4,247	6,636	5,309	4,247

- Early testing of the CH unit together with early exploration of the TS unit -- This feature would tend to result in earlier completion of characterization testing which, in turn, would result in lower indirect program costs.

- ESF access by east-to-west ramps only -- This feature appears to reduce the impacts on historical properties.

In addition, it was possible to identify the following feature of an option that tended to be associated with comparatively higher consequences:

- Tuff ramp located in the north end of the repository block. This feature appears to have comparatively the greatest adverse impact on historical properties.

5.0 ASSESSMENT OF THE MULTIATTRIBUTE UTILITY FUNCTION

Sections 3 and 4 of this volume described the probabilities and consequence estimates needed for the construction of the decision tree. This section presents the remaining input for the tree, the multiattribute utility function. The techniques used to develop the multiattribute utility function for valuing scenarios and the results of the valuation are described here.

5.1 Overview

A multiattribute utility function is a model of the value structure used to evaluate decision consequences. The process for constructing this value model is the same as that used to construct any other model, such as a model for groundwater flow. Three essential steps are required: (1) postulating a potentially reasonable model form, (2) testing whether the assumptions underlying the postulated model form are reasonable, and (3) estimating numerical values for the parameters of the model.

An additive multiattribute utility function (Equation 2-9) was postulated as the functional form for the value model. As described in Section 2.4.3, in order that the additive form be reasonable, a condition called additive independence must exist among the performance measures, X_i.

5.1.1 Independence Assumptions

Several different types of independence assumptions are important for multiattribute utility analysis. One type, which is relevant for problems that do not involve uncertainty, is called preferential independence. With preferential independence, the decision makers' preferences for specific levels of a performance measure do not depend on the levels of the other measures. More precisely, two performance measures X and Y, are said to be preferentially independent of other performance measures if preferences for changes involving levels of X and Y do not depend on the levels of other measures. For analyses that do not involve uncertainty, preferential independence is sufficient to ensure the additive form (Keeney and Raiffa, 1976).

When the analysis accounts for uncertainty in performance measure levels, as this study does, preferential independence is a necessary, but not a sufficient condition for an additive utility function. In this case, additive independence of performance measures, a slightly more complicated type of independence assumption, is necessary. Performance measures $X_1,...,X_n$ are said to be additive independent if the decision-makers' preferences for lotteries involving outcomes for any single measure do not depend on the outcomes of the other measures.[12] If preferences are additive independent, then the decision-makers' preference-order for lotteries involving performance measures does not depend on the joint probability distributions of the lotteries, but only on their marginal distributions.

5.1.2 Tests for Checking Independence Assumptions

Independence assumptions, such as preferential independence and additive independence, are tested by looking for specific cases of preferences that contradict the independence assumption. If none are found, the assumption is assumed to be appropriate.

To determine the appropriateness of preferential independence, outcomes are specified in terms of differing levels for pairs of performance measures. For simplicity, all of the other measures are assumed to be held constant. For example, the following pairs might be considered of equal preference -- zero nonradiological worker fatalities with postclosure releases at 10 percent of the EPA standard versus 20 nonradiological worker fatalities with zero postclosure releases. If such indifference pairs do not depend on the levels of other performance measures, such as costs, then the measures may be assumed to be preferentially independent of the other measures.

To test the appropriateness of the additive independence assumption, pairs of lotteries with identical marginal probability distributions are presented to decision makers. Again, all of the other performance measures are assumed to be fixed. Figure 5-1 illustrates such a lottery pair. In both lotteries, there is an equal chance that the

[12] An example of a lottery involving a performance measure (releases) is a gamble wherein there is a 0.5 probability that the repository will produce releases equal to 0.1 times the EPA standard, and a 0.5 probability that will produce releases equal to 1.0 times the EPA standard.

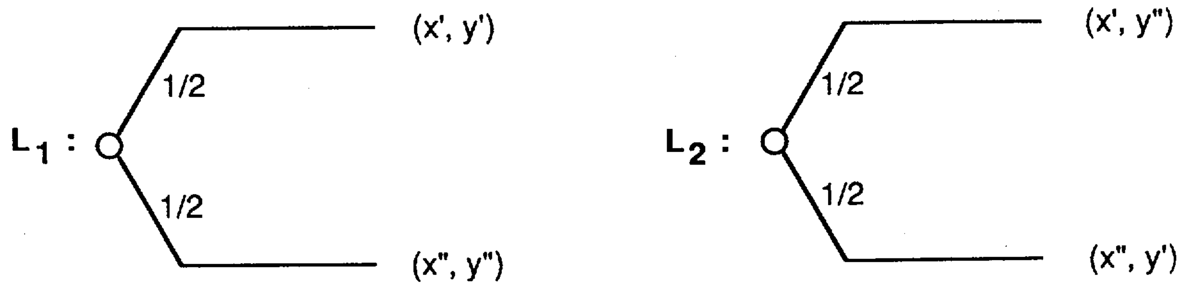

Figure 5-1. Test Used to Verify Additive Independence

outcomes for performance measures X and Y would be either x' or x" and y' or y", respectively. The only difference between the two lotteries is the manner in which the combinations of the outcomes occur. With the first lottery, the outcomes are either x' and y' or x" and y". With the second lottery, the outcomes are either x' and y" or x" and y'.

For example, the decision makers might be told to assume that the outcomes of all performance measures, except nonradiological worker fatalities and postclosure releases, are fixed. The performance measures X and Y, in this case, would correspond to worker fatalities and postclosure releases, respectively. The outcomes x' and x" would correspond to low and high outcomes for worker fatalities, respectively. Similarly, the outcomes y' and y" would correspond to low and high outcomes for releases, respectively. Figure 5-2 illustrates two such lotteries. Lottery L1 would be a 50 percent chance that developing the repository would produce low nonradiological worker fatalities and low releases versus a 50 percent chance that developing the repository would produce high nonradiological worker fatalities and high releases. Lottery L2 would be a 50 percent chance that developing the repository would produce low worker fatalities and high releases, and a 50 percent chance that developing the repository would produce high worker fatalities and low releases. If decision makers do not feel a preference for one of the lotteries over the other, worker fatalities and releases are additive independent.

As another example, suppose that the test were applied to check additive independence involving two different measures -- probability of regulatory approval and nonradiological worker fatalities. Lotteries L1 and L2 illustrate this example as shown in Figure 5-3. Lottery L1 would be a 50 percent chance of an outcome wherein the repository design has a low probability of regulatory approval and constructing the

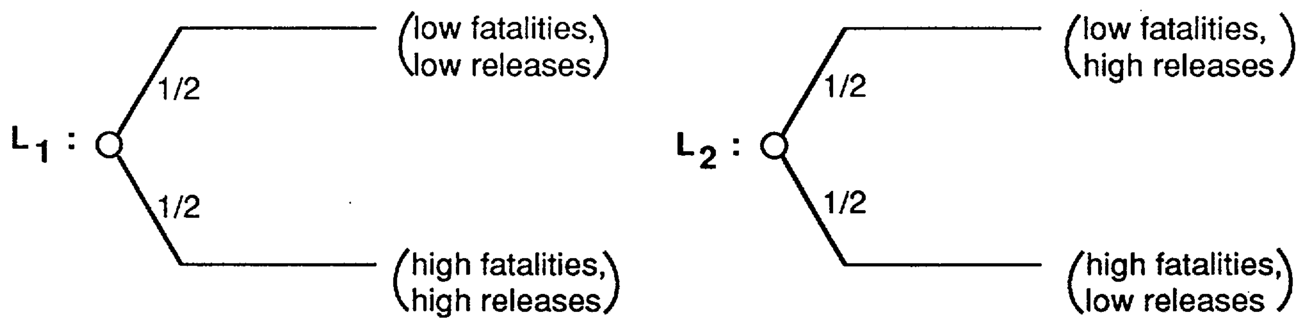

Figure 5-2. Two Lotteries With All Performance Measures Fixed Except Nonradiological Worker Fatalities and Postclosure Releases

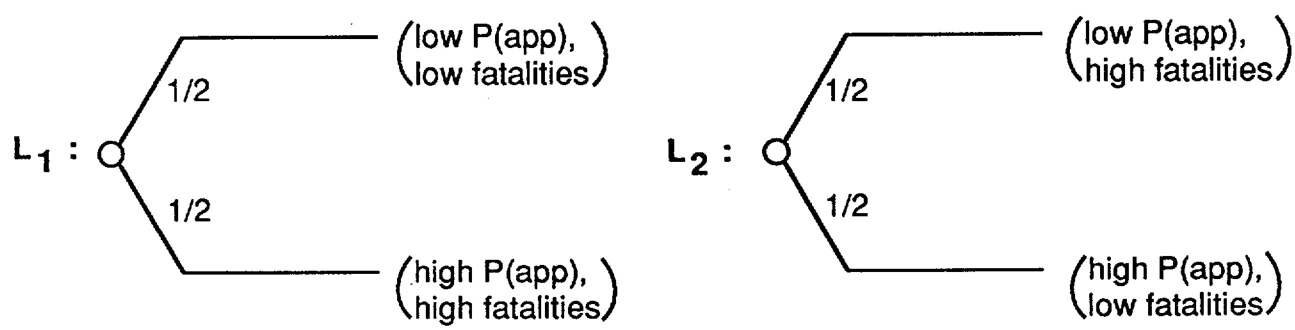

Figure 5-3. Two Lotteries With All Performance Measures Fixed Except Nonradiological Worker Fatalities and the Probability of Regulatory Approval, P(app)

repository would produce low worker fatalities, and a 50 percent chance of an outcome wherein the repository design has a high probability of approval and constructing the repository would produce high worker fatalities. Because the repository is not likely to be developed if the probability of regulatory approval is low, this lottery essentially implies a 50 percent chance of a repository with high worker fatalities. Lottery L2 would be a 50 percent chance of an outcome wherein the repository design has a low probability of regulatory approval and constructing the repository would produce high worker fatalities, and a 50 percent chance of an outcome wherein the repository design has a high probability of regulatory approval and constructing the repository would produce low worker fatalities. In this case, the lottery essentially implies a 50 percent chance of a repository with low worker fatalities. Lottery L2 is obviously preferable to Lottery L1, so probability of regulatory approval and nonradiological worker fatalities are clearly not additive independent. This illustrates again why a decision tree, rather than a multiattribute utility function, was used to account for performance measures, such as probability of regulatory approval, that do not pass the additive independence test.

5.2 Assessment of the Multiattribute Utility Function

This section presents the details of the assessment of the multiattribute utility function. The text is organized into five subsections. The discussion begins with a description of the methods used for the assessment. The functional form proposed for the utility function is then discussed and the necessary independence assumptions verified. This is followed by the assessments of the single-attribute utility functions, and the assessments of the value tradeoffs to specify the scaling factors.

5.2.1 Source of Value Judgments Used for the Assessment

Most of the value judgments necessary for constructing the multiattribute utility function were provided by members of the Management Panel. The members of this panel had responsibility to advise the Director of DOE's OCRWM regarding the choice of an ESF-repository option. The members of the Management Panel and their qualifications are listed in Appendix A.

Due to schedule conflicts among the members of the Management Panel, it was not always possible to convene the entire panel for each step of the development of the multiattribute utility function. Consequently, some meetings were held with subsets of the panel, rather than with all panel members. When subsets of the panel were responsible for conducting various steps of the process, the results were then reviewed at subsequent meetings to ensure that panel members who were not present agreed with the results produced by those members who were present.

5.2.2 Form of the Multiattribute Utility Function

The following special form of the additive utility function was selected:

$$U(X_1,\ldots,X_8;B) = B - \sum_{i=1}^{8} k_i \bullet C_i(X_i) \qquad \text{(Eq. 5-1)}$$

In this equation, B is the equivalent economic benefit associated with a scenario. For example, for Scenario A, B is the benefit of having a closed repository, expressed in dollars. For Scenarios B through F, benefit B is assumed to be zero. The C_i are component disutility functions for the performance measures X_i, $i = 1, ..., 8$; and the k_i are positive scaling factors representing value tradeoffs between units of the corresponding performance measures and costs. The component disutility functions account for the relative desirability of achieving higher versus lower scores for each consequence measure. The scaling constants determine the relative importance of achieving a given score on one measure versus achieving a score on another. Because the selected form of the utility function expresses utility in units of dollars, the utility measure could be interpreted as net benefit, expressed in equivalent dollars.

Specifying the parameters of Equation 5-1 required specifying the disutility functions C_i and the scaling factors k_i.

5.2.3 Independence Checks

The consequence measures were deliberately defined to ensure that the condition of additive independence would hold. As noted previously, the consequence measures reflect fundamental objectives. Where possible, direct measures were defined for measuring performance. Whenever the objectives specified for a utility function are fundamental and measured by direct performance measures, there is a sound basis for an additive utility function (Keeney, 1981).

Indeed, the consequence measures defined for this analysis were nearly identical to those used in the earlier application of multiattribute utility analysis to compare alternative sites that had been nominated as suitable for characterization (see Section 1.4). Detailed tests that verified the additive independence assumption for measures of preclosure health and safety, environmental impact, costs, and postclosure releases were applied in the earlier study.

Given that these previous tests had already verified additive independence assumptions, only cursory checks were applied, based on the methods described in Section 5.2.1 and using a subset of the Management Panel, to re-evaluate the assumption. Attention was concentrated on the measures related to impacts on aesthetics and on historical properties, since the constructed scales for these measures differed from the similar measures defined for the earlier MUA of nominated sites.

As an example of the independence tests applied, a member of the Management Panel was asked to consider whether a point of indifference established between two performance measures, aesthetic degradation and impacts on historical properties, depended on a third performance measure, nonradiological fatalities to workers. Table 5-1 illustrates the outcomes of two hypothetical options, labeled A and B, that were judged to be indifferent. The panel member was then asked to assume that the number of worker fatalities occurring under each option was reduced from 12 to zero. The panel member indicated that this change did not alter his indifference between the two options. This indicated that the performance measures for aesthetic impact and historical properties, X_5 and X_6, were preferentially independent of the performance measure for worker fatalities, X_4. Furthermore, when asked whether he had given any thought to the specific levels of the other performance measures, the panel member indicated that he had not. This indicated that the levels of other performance measures were of no concern when making the value tradeoff between aesthetic impact and historical properties. This test, therefore, established the preferential independence of performance measures X_5 and X_6.

TABLE 5-1

ELICITATION OF PREFERENCES FOR INDEPENDENCE TESTS

Option A			Option B			
Aesthetics	Hist. Prop. Sites	Fatalities	Aesthetics	Hist. Prop. Sites	Fatalities	One Panel Member's Preference
12	3 ha	12	4.5	0 ha	12	Indifferent

To verify additive independence, the panel member's relative preferences were investigated for outcomes involving specified numbers of worker fatalities versus lotteries involving chances of higher numbers of worker fatalities. The results indicated that the panel member was indifferent to the choice between a lottery involving a probability of a number of worker fatalities and the certainty of a number of fatalities equal to the expected value of the lottery. Furthermore, this indifference did not depend on the level of other performance measures. This result, coupled with the preferential independence of performance measures, was sufficient to verify that the utility function must be either additive or multiplicative, and the additive form was verified to be the correct choice. (For a proof of the validity of this approach, see Keeney, 1976.) .

5.2.4 Component Disutility Functions

The process for developing the component disutility functions depended on the consequence measure. Because the earlier application of MUA to nominated sites used many of the same natural measures as the current study, the single-attribute utility functions developed for that study were useful inputs for the current effort. In particular, the earlier study concluded that the component disutility functions for fatalities, costs, and postclosure releases were all linear. The earlier study did not include person-rem exposures as a performance measure; however, an argument for a linear utility function for this measure could also be made -- because cancer fatalities are often assumed to be linearly related to exposures, a utility function that is linear in cancer fatalities should be linear in person-rems of exposure.

The linearity assumption for the component disutility functions for these measures was verified by the Management Panel through a process wherein test questions involving direct assessments were presented to the Panel. In all cases, these assessments confirmed that component disutility functions for person-rem exposures (measures X_2 and X_3), fatalities (measure X_4), and costs (measures X_7 and X_8) were linear.

It was not surprising that the Management Panel agreed with the assumption of linearity. For example, if the linearity assumption did not hold between the cost and fatality consequence measures, it would imply that the amount of money one would spend to reduce the number of fatalities from ten to five would be different from the amount of money one would spend to reduce the number of fatalities from five to zero.

If a component disutility function is linear, then the performance measure itself provides a measure of the desirability of the outcome. Thus, the component utility functions (C_i) for releases, person-rem exposures, fatalities, historical properties, and costs are all identity functions, i.e., $C_i(x_i)=x_i$, for $i=1,2,3,4,6,7$, and 8. The component functions were called disutility functions because larger numbers of fatalities, releases, costs, etc., are always less desirable. Accordingly, they were subtracted from benefits, *B*, as shown in Equation 5-1.

The component disutility functions for environmental aesthetics and impacts on historical properties were assessed using formal utility elicitation methods. The source of the component disutility function for aesthetic impacts was, as usual, the Management Panel. Although specification of a component disutility function for aesthetic impacts would necessarily involve some technical knowledge, the Management Panel was relatively well-informed regarding people's concerns over aesthetic impacts and the visual impact characteristics that would be of most importance to those who would see the site.

In the case of impacts on historical properties, however, the Expert Panel on Archaeological and Historical Properties, rather than the Management Panel, was the source of the disutility function. The major concern when mitigating historical properties is the potential loss of scientific information. Because judging this loss would involve significant specialized technical expertise, the Management Panel elected to review and concur with the disutility function that was developed by the Expert Panel.

The formal elicitation methods used to assess component disutility functions for aesthetic impacts and impacts on historical properties involved asking panel members a series of tradeoff questions, examples of which are provided below. In all cases, each panel member was asked to provide his own judgment first. An open discussion of the value judgments then followed to resolve disagreements to the degree appropriate (i.e., when the reasoning of one member seemed appealing to another). There was no attempt to force consensus on the appropriate functional form. The goal was to reach agreement on a disutility function thought to be a reasonable basis for conducting a nominal analysis. Panel members were assured that any significant differences in value judgments could be addressed through sensitivity analysis.

The elicitation method consisted of assessing a measurable value function, using the midpoint method (Chankong and Haimes, 1983), and then verifying that the measurable value function qualifies as a utility function.[13] Finally, the utility function was inverted to obtain a disutility function. The method of assessment involved successively identifying scores for the performance measure whose values (desirabilities) are halfway between already-established values.

To illustrate, a measurable value function for aesthetic impacts was constructed as follows. For aesthetic impacts, the scale has 13 levels -- with level 12 corresponding to no impact and level zero to the greatest impact (see Table 2-2). The value function was scaled from zero to 100, whereupon a value of zero was assigned to a level zero impact, and a value of 100 to a level 12 impact. Tradeoff questions involving various scores between zero and 12 were posed to identify a score corresponding to a value of 50. For example, the panel was asked to consider the value gained by increasing the score of an option from zero to 6 as compared with the value gained by increasing the score from 6 to 12. The panel response was that more improvement was gained by increasing the score from zero to 6 than by increasing the score from 6 to 12. The reason for this derives from the definitions associated with the scores. The panel felt that the consequences of a score of zero (skyline structures, structures and facilities, and roadcuts and traffic visible from multiple vantage points) would be extremely detrimental. On the other hand, the incremental improvement gained by removing visible roadcuts and traffic was judged to be small relative to removing visible skyline structures and facilities.

Similar tradeoff questions were posed until the panel estimated that the situation described by a score of 4 would have a value of 50; in other words, the value gained from increasing the aesthetics score from zero to 4 was indeed approximately the same as the incremental improvement gained by increasing the score from 4 to 12.

A series of similar tradeoff questions led panel members to identify the score whose value is midway between the values established for scores of zero and 4 (a score of 1), and the score whose value is midway between the values established for 4 and 12 (a score of 7). Similarly, other tradeoff questions were used to establish the values to be

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13 A measureable value function is similar to a utility function, but, unlike a utility function, does not necessarily apply when uncertainty over outcomes is considered.

assigned to other scores. The results imply the value function for aesthetic impacts shown in Table 5-2.

TABLE 5-2

SCORES AND CORRESPONDING UTILITIES FOR THE OBJECTIVE "MINIMIZE AESTHETIC DEGRADATION"

Score, x_5	Utility, U_5
0	0
1	25
2	35
3	45
4	50
5	65
6	70
7	75
8	80
9	85
10	90
11	95
12	100

Figure 5-4 shows the plot of the value function for aesthetic impacts. The disproportionate increases in value between the aesthetic scores of zero and 1 and between 4 and 5 reflect the panel's judgment that removing skyline structures improves the aesthetic quality of the site significantly more than removing roadcuts or surface facilities.

As described in Section 2.4.2, the performance measure scale for impacts on historical properties was expressed in terms of the weighted areal extent of historical property sites that must be mitigated. Application of the elicitation techniques quickly brought to light the fact that panel members viewed the value function to be linearly proportional to the performance measure. Linearity of preferences means that the performance measure for degradation of historical properties serves as its own disutility function.

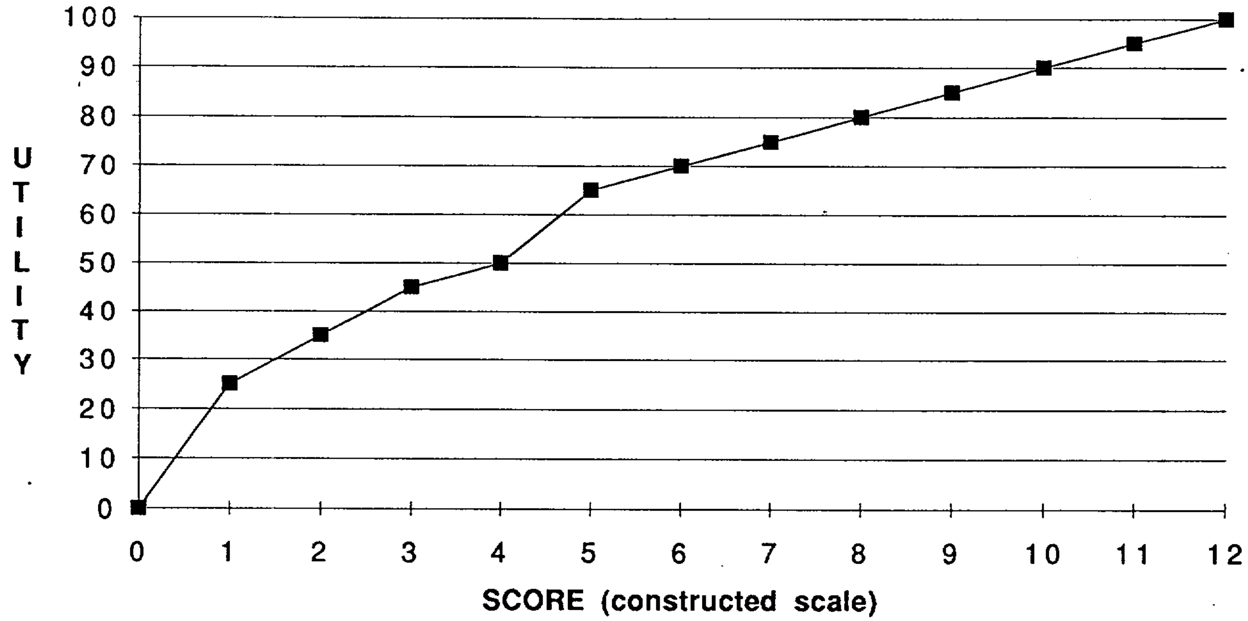

Figure 5-4. Utility Function for Aesthetic Impacts

Table 5-3 summarizes the complete set of component disutility functions derived from the Management Panel, using the nomenclature established by Equation 5-1. Since Equation 5-1 requires disutility functions, rather than utility functions, the value function for aesthetic impacts was inverted, as shown in the table, so that higher disutilities indicates less desirable outcomes. The table also shows the ranges of the performance measures, which were chosen to be broad enough to include all possible levels estimated for all of the candidate ESF options.

5.2.5 Scaling Factors

The scaling factors used, denoted by k_i in Equation 5-1, were meant to reflect the relative values of achieving favorable performance on the various measures. The numerical values for the tradeoff factors were determined by the value tradeoffs that decision makers were willing to make between the various pairs of measures. The Management Panel was the source of all tradeoff values.

TABLE 5-3

PERFORMANCE MEASURES AND COMPONENT DISUTILITY FUNCTIONS

Performance Measure	Symbol	Units	Impact Range: Lowest Level	Impact Range: Highest Level	Component Disutility Function C
Postclosure Releases (C14 + aqueous)	X1	EPA standard	0	2	C1(x1) = x1
Radiological Worker Health	X2	person-rems	0	40	C2(x2) = x2
Radiological Public Health	X3	person-rems	0	2×10^{-4}	C3(x3) = x3
Nonradiological Worker Safety	X4	fatalities	0.5	28	C4(x4) = x4
Aesthetics	X5	constructed scale	0	12	C5(12) = 0
					C5(11) = 5
					C5(10) = 10
					C5(9) = 15
					C5(8) = 20
					C5(7) = 25
					C5(6) = 30
					C5(5) = 35
					C5(4) = 50
					C5(3) = 55
					C5(2) = 65
					C5(1) = 75
					C5(0) = 100
Historical Properties	X6	hectares	0	7	C6(x6) = x6
Direct Costs	X7	discounted dollars	75 M	1800 M	C7(x7) = x7
Indirect Costs	X8	discounted dollars	850 M	7200 M	C8(x8) = x8

The specific form selected for the additive multiattribute utility function (Equation 5-1) required the tradeoffs to be expressed in dollars per unit of the corresponding component disutility function. However, tradeoffs can be assessed between any two measures and, through simple algebra, can be expressed in terms of any other measure. In practice, the measures for structuring tradeoff questions were selected to minimize the difficulty of making the required judgments, and the preferences of the Management Panel were sought in choosing the most convenient tradeoff questions. In the case of several measures, information on the tradeoff values used in other contexts was available. In all of such cases, this information on tradeoff values was expressed in dollars. Therefore, dollar tradeoffs were often the most convenient form for the elicitation.

The general process for eliciting scaling factors can be illustrated by the methods used to assess the factors for the measures defined for aesthetic impacts and impacts on historical properties. The tradeoff between the two measures was assessed by examining the panel member preferences for improving the aesthetic impact score versus improving the score for impacts on historical properties. The example given here describes the results obtained from one panel member in one meeting of the panel. The preferences of other panel members attending the meeting were obtained in a similar way, and subsequent meetings were held to obtain the preferences of other members of the Management Panel. As in the case of the assessment of component utility functions, panel members were asked if they could agree on a single tradeoff value for use in the base case analysis. When a panel member did not agree with the majority view, alternative tradeoff values were obtained for use in sensitivity analyses.

The process involved asking each panel member to consider various pairs of hypothetical options, labeled A and B, wherein each option had identical scores for all measures but two. The scores for the performance measures that differ between the pairs were then described. Each panel member was then asked to independently state his preference over the various pairs of options. Table 5-4 summarizes some of the option pairs that were used and the preferences indicated by one panel member.

In the first comparison, labeled Comparison 1, Option A was defined to be an option having an aesthetic impact score of zero, indicating the worst possible aesthetic impact (skyline structures, buildings, roadcuts and traffic visible from múltiple vantage points). The option was also defined as having an impact on historical property sites score of

TABLE 5-4

PREFERENCES OF ONE MANAGEMENT PANEL MEMBER FOR TRADEOFFS BETWEEN AESTHETIC IMPACT AND HISTORICAL-PROPERTY SITE DEGRADATION

Comparison Number		Option A: Aesthetics [0-12 scale]	Option A: Historical Property Sites [hectares]	Option B: Aesthetics [0-12 scale]	Option B: Historical Property Sites [hectares]	One Panel Member's Preference
1	Score	0	0	12	7	B
	(Disutility)	(100)	(0)	(0)	(7)	
2	Score	11	0	12	7	A
	(Disutility)	(5)	(0)	(0)	(7)	
3	Score	0	0	12	4	B
	(Disutility)	(100)	(0)	(0)	(4)	
4	Score	8	0	12	7	Indifferent
	(Disutility)	(20)	(0)	(0)	(7)	

zero hectares, indicating no incremental impact whatsoever. Option B was defined as having an aesthetic impact score of 12, indicating no aesthetic impacts whatsoever, and an incremental impact on historical properties of 7 hectares. As indicated in the table, the panel member expressed a preference for Option B. Roughly speaking, this result indicated that the panel member felt that it was more important to avoid serious adverse aesthetic impacts than to avoid the highest possible impact on historical property sites.

Three additional comparisons of hypothetical options numbered 2 through 4, are also shown in Table 5-4. As indicated, the panel member concluded that he was indifferent between the two options in Comparison 4.

If the panel member is indifferent between two options, the utilities of those options must be equal. Because of additive independence, the utility function must be linear and, therefore, can be expressed in the form of Equation 2-9. Furthermore, because the options were assumed to be identical in all respects except aesthetic impacts and degradation of historical properties, the scaling factors must satisfy the equation

$$k_5C_5(x_{5A}) + k_6C_6(x_{6A}) = k_5C_5(x_{5B}) + k_6C_6(x_{6B}) \qquad \text{(Eq. 5-2)}$$

where

k_5 = scaling factor for aesthetic quality ($/utile)
k_6 = scaling factor for historical-property sites ($/ha)
C_5 = aesthetic-quality disutility function (utiles)
C_6 = historical-property site disutility function (ha)

The point of indifference expressed by the panel member implied the following relationship:

$$k_5C_5(8) + k_6C_6(0) = k_5C_5(12) + k_6C_6(7)$$

$$= k_5 \bullet 20 \text{ utiles} + k_6 \bullet 0 \text{ ha} = k_5 \bullet 0 \text{ utiles} + k_6 \bullet 7 \text{ ha}$$

Collecting terms provides a quantitative measure of the tradeoff between aesthetics (X_5) and historical-property site degradation (X_6):

$$k_6 = (20 \text{ utiles}/7 \text{ ha}) \bullet k_5$$

To obtain scaling factors expressed in dollars, panel members were asked to indicate a tradeoff value between aesthetic impact and cost. Using the same method as described above, each panel member was asked to express his preference between option pairs that differed only in their aesthetic impact scores and costs. In each case, the lower cost option was assumed to have the best possible aesthetic score (score of 12) and the higher cost option the worst possible aesthetic impact score (score of zero). The point of indifference, therefore, would be a cost difference that indicated the panel member's maximum willingness to pay for eliminating worst possible aesthetic impacts. To ensure that the cost tradeoffs would be expressed in current dollars, the panel members were asked to assume that the additional cost of the option with the lower aesthetic impact had to be paid immediately.

The resulting cost tradeoff, provided by the panel member, was approximately $4 million. Using this result, and Equation 5-2 above, the scaling factors for this panel member were

$$k_5 = \$4M/100 \text{ utiles} = \$40K/\text{utile}$$
$$k_6 = (20 \text{ utiles}/7 \text{ ha}) \times \$40K/\text{utile} = \$114K/\text{ha}$$

Tradeoff values for other measures were obtained in a similar fashion. However, in many cases, cost tradeoffs used in other contexts provided important inputs to the panel's deliberations. For example, in providing a cost tradeoff for health effects, guidance from the NRC in the mid 1970's was used (NRC, 1983). This guidance suggested that the cost tradeoff for avoidance of radiation-induced cancer fatalities should be $1000 per person-rem avoided. Taking inflation into account, the panel elected to select a cost tradeoff of $4,000 per person-rem avoided.

To help assess a tradeoff for postclosure releases, the following logic was used. According to an EPA calculation (EPA, 1987), releases from a repository at the level specified by the limit in the standard were roughly estimated to produce 700 additional cancer fatalities in 10,000 years. Thus, the tradeoff value for releases at the EPA limit should be about 700 times the statistical value of life assumed. The Management Panel suggested that a statistical value of life of $5 million be used for the nominal analysis. Thus, the nominal scaling factor assumed for postclosure releases, k_1, is (700 x $5M=) $3.5 billion.

Similar considerations formed the basis for other scaling factors. For example, a scaling factor of $1.25M/worker fatality was selected based on roughly similar values used in other applications (Graham and Vaupel, 1981). A discount rate of 10 percent per year was used to discount costs (direct and indirect) that would occur in future years. Impacts other than costs were not discounted.

Table 5-5 summarizes the scaling factors established by the Management Panel. The best-judgment values were used for the nominal analysis. The low and high values were used in sensitivity analyses.

5.3 Alternative Forms for the Utility Function Reflecting Risk Aversion

The multiattribute utility function (Equation 5-1) reflects a neutral attitude towards risk taking. The preference judgments expressed by the Management Panel indicated that panel members were indifferent to the choice between choosing a lottery wherein different net benefits result with different probabilities, and choosing a certain net benefit equal to the expected value of the lottery. Risk preference neutrality was similarly assumed in the previously cited application of MUA to evaluating alternative sites for the repository.

TABLE 5-5

SCALING FACTORS

Measure	Units	Scaling Factor: Low	Scaling Factor: Best Judgment	Scaling Factor: High
Postclosure Releases	EPA standard	$350 M	$3.5 B	$35 B
Radiological Worker Health	person-rems	$400	$4,000	$40,000
Radiological Public Health	person-rems	$400	$4,000	$40,000
Nonradiological Worker Safety	fatalities	$100 K	$1.25 M	$10 M
Aesthetics	constructed scale	$400 K	$4 M	$40 M
Historical Properties	hectares	$100,000	$200,000	$2,000,000
Direct Costs	discounted dollars	0%	10%	20%
Indirect Costs	discounted dollars	0%	10%	20%

Risk aversion is sometimes assumed as an alternative to risk neutrality. A decision maker who is risk-averse will prefer the expected value of a lottery to the lottery itself. Risk aversion is a common attitude for personal decisions involving fairly significant gambles. To check whether or not someone is personally risk-averse, the person can be asked whether he/she would prefer a 50/50 gamble of winning $1,000 or nothing, versus receiving $500 for certain. If the person is indifferent, he/she is risk-neutral. If the person prefers the $500, that person is risk-averse. Many people would prefer the expected value of a lottery to the lottery itself. In fact, many people might well choose $300 for certain over a lottery offering a 50/50 chance of $1,000.

The Government makes many decisions involving uncertain outcomes. If the Government consistently chooses low-risk options worth less than the expected values of options with higher risk, then the public might be worse off over the long run. The effect would be the same as that resulting from a risk-averse individual repeatedly being offered the choice between a 50/50 lottery for $1,000 and a guaranteed $300. If the offer is made only once, choosing the $300 might make sense. However, if the choice is offered over and over again, choosing the 50/50 lottery would yield $500 per choice on average, which would be better than $300 available from choosing the sure thing. This observation might serve to argue that the government should be risk neutral.

Although the Government makes many decisions involving uncertain health and environmental outcomes, no other decision is exactly like the ESF-repository option choice. The argument for risk neutrality, therefore, is not totally convincing. For the purposes of sensitivity analysis, it is useful to investigate the effect of assuming alternative attitudes towards risk-taking.

Alternative risk attitudes can be investigated by treating the utility function of Equation 5-1 as a measurable value function and superimposing a risk-averse attitude on the resulting value measures.[14] The following exponential form does this:

$$U_{risk} \quad (Y) = A + B \exp(-Y|R) \qquad \text{(Eq. 5-3)}$$

with $Y = U(X_1,...,X_8)$. In this equation, A and B are scaling constants, $Y = U(X_1,...,X_8)$ is the utility function of Equation 5-1, and R is a positive constant called risk tolerance. The smaller the number R (expressed in dollars) is, the more risk aversion is implied by Equation 5-3.

To investigate the effect of risk aversion, sensitivity analyses, described in the next section, were conducted using the alternative utility function form shown in Equation 5-3.

14 See the previous footnote (in Section 5.2.4) regarding measurable value functions.

6.0 RESULTS AND SENSITIVITY ANALYSIS

The multiattribute utility function (Equation 5-1) is the last element needed to complete the construction of the decision tree, which, as explained in Section 2, is the model used to evaluate and rank the 34 ESF options. The utility function was used to compute the net benefit of each scenario for each option. The calculations were conducted using the consequence estimates in Section 4 and the disutility functions and scaling factors in Section 5. (Refer to Appendix C for details of the calculations.) The decision tree was completed when the resulting net benefit estimates were added to the decision tree, and the probability estimates of Section 3 for the scenarios were also appended. The resulting completed decision tree showed, for each ESF option, not only how likely each scenario was, but also how desirable that scenario would be.

Figure 6-1 illustrates the completed decision tree for Option 1 (base case). The probabilities for the various events in the tree are displayed under the corresponding branches in the tree. The net benefit of each scenario, expressed in terms of dollar equivalents, is displayed adjacent to the end points on the tree that correspond to the scenarios. The net benefits for five of the six scenarios are negative, because only adverse impacts (e.g., health and safety impacts, environmental degradation, costs, etc.) would occur for scenarios in which the site would be abandoned. Scenario A, however, also produces a positive benefit (a closed repository). Therefore, in accordance with the utility function (Equation 5-1), an amount B, representing the equivalent economic benefit of having a closed repository, was added to the equivalent economic consequences for Scenario A. Depending on the value of B, therefore, the net benefit estimate for Scenario A might be positive.

No attempt was made to estimate B, the equivalent economic benefit of a closed repository. The reason for this, to be demonstrated below, was that the relative ranking of options does not depend strongly on the value that is assigned to B, so long as this value is high enough to justify the repository program. For the purposes of the nominal analysis, an arbitrary benefit of $50 billion was assumed.

A completed decision tree, such as that shown in Figure 6-1, is "solved" by computing its expected utility, which, in this case, means weighting the net benefits associated with each scenario by the probability of the scenario and adding the results. The probability

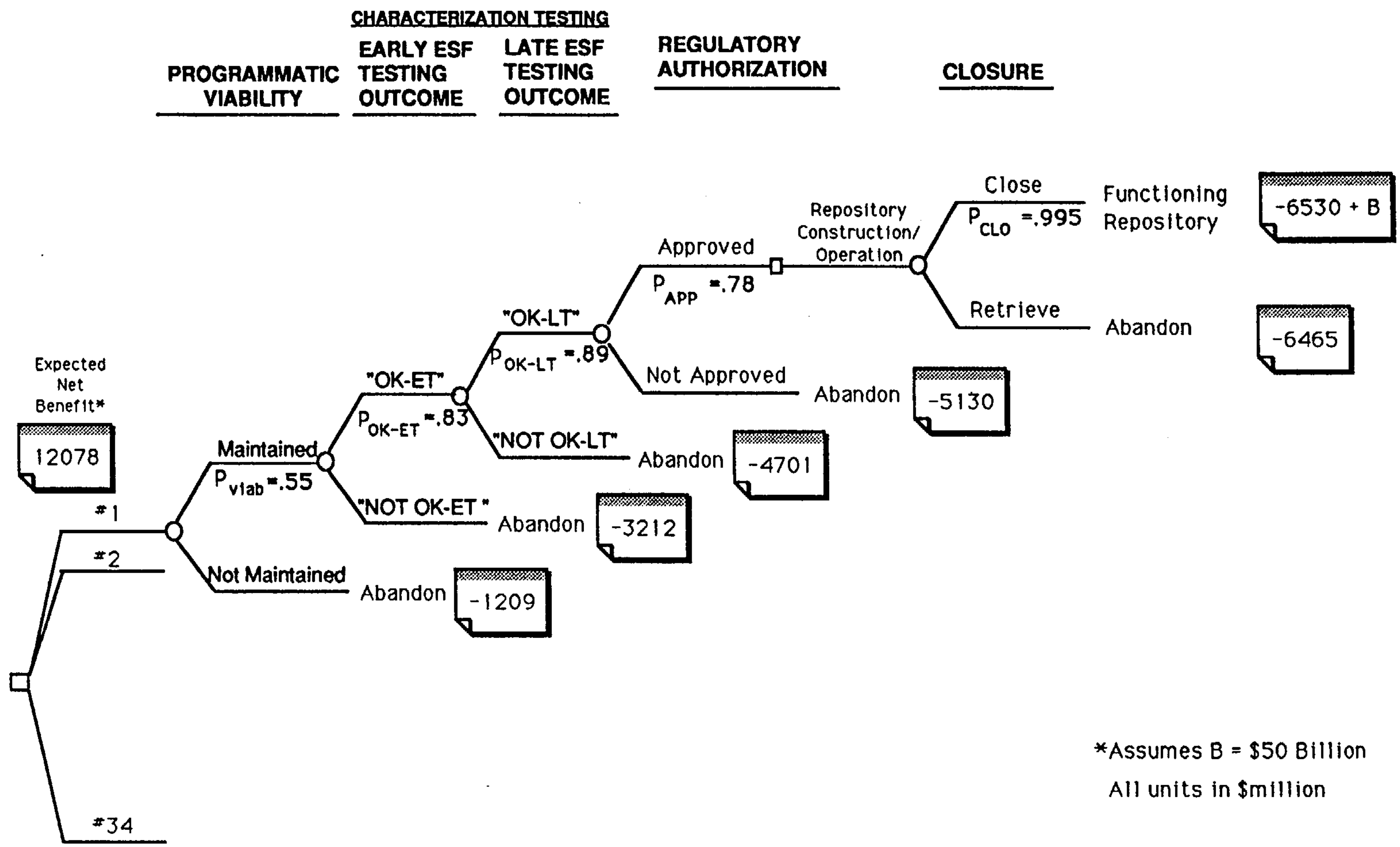

Figure 6-1. Completed Decision Tree for Option 1

of each scenario is the product of the probabilities (under the branches) of the events that define the scenario. The result for Option 1, expressed in equivalent economic dollars and assuming a benefit of $50 billion for a closed repository, was $12,078 million. This value is shown on the left-hand-side of the tree above the branch corresponding to Option 1.

6.1 Ranking of the Options

Table 6-1 shows the expected net benefits computed for all 34 options, with the options ordered in terms of their expected net benefits. Appendix C contains the detailed calculations involved. As indicated in Table 6-1, Option 30 was computed to have the highest expected net benefit, $24,411 million.

Figure 6-2 shows the underground layout for Option 30. There would be four accesses. Two 25-foot ramps would access the MTL, located in the southern corner of the repository block and having a relatively large area. The ramp from the southeast would be used for muck handling, and the one from the northeast used to provide men and materials service. Both ramps would function in science, ventilation, and emergency egress capabilities. The two additional accesses for the repository consist of a 25-foot diameter mechanically mined men-and-materials shaft in the south and a 25-foot diameter mechanically mined emplacement exhaust shaft in the north. Unlike other configurations, there would be no direct gravity flow pathway from the TS unit to the CH unit.

Figure 6-3 shows the expected net benefits of the options displayed in bar-chart form. As illustrated, there is a fairly smooth distribution between the highest and lowest values. The six top-ranked options, however, stand out slightly from the rest. These top six correspond to the three Option Pairs, 6 and 23, 7 and 24, and 13 and 30.

As the twin of Option 30, Option 13 has a similar physical configuration (but would include an internal shaft access from the TS unit to the CH unit) and construction method, but uses the original SCP test strategy. Figure 6-4 shows the layout for Option Pair 6 and 23. There are again four accesses in total, and the configuration is similar, but drill-and-blast construction would be used for both the MTL and repository. Like Option Pair 13 and 30, two 25-foot diameter TBM ramps would access the ESF, but in

TABLE 6-1

**RANK ORDER OF 34 ESF OPTIONS
WITH RESPECT TO THEIR EXPECTED NET BENEFITS**

Overall Ranking	Option	Expected Net Benefit* ($ millions)
1st	30	24,411
2nd	23	23,369
3rd	24	23,046
4th	13	22,659
5th	6	22,270
6th	7	22,003
7th	2	20,841
8th	19	20,436
9th	25	19,933
10th	4	19,695
11th	21	19,611
12th	28	19,235
13th	22	17,772
14th	29	16,968
15th	32	16,770
16th	27	16,373
17th	20	16,342
18th	8	16,024
19th	31	15,886
20th	15	15,467
21st	33	15,214
22nd	5	14,510
23rd	12	13,791
24th	3	13,673
25th	16	13,664
26th	11	13,547
27th	1	12,078
28th	14	11,381
29th	10	11,170
30th	18	10,995
31st	17	10,979
32nd	34	9,846
33rd	26	7,704
34th	9	6,163

*Assumes benefit of a functioning repository is $50 billion.

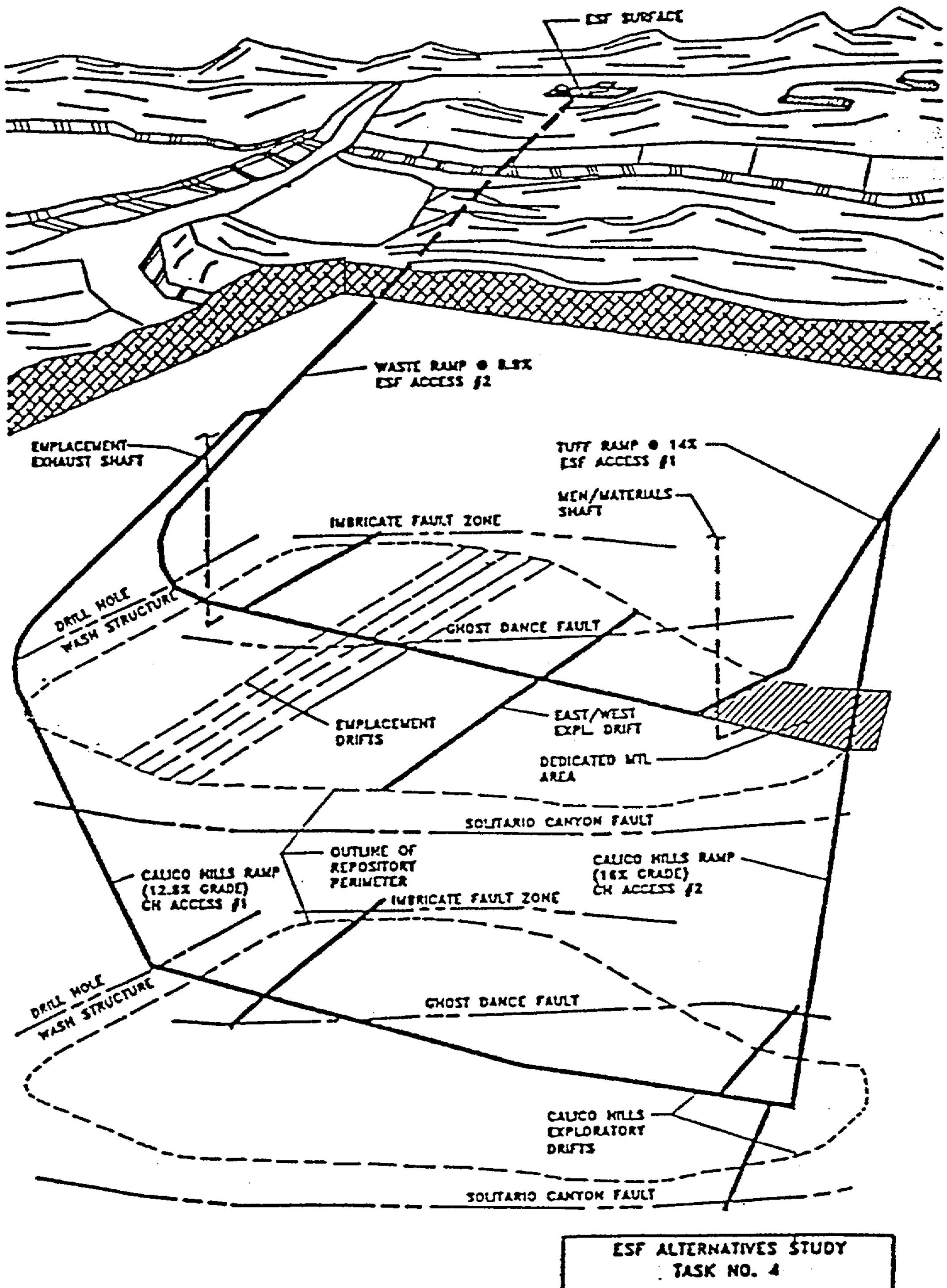

Figure 6-2. Underground Layout for Option 30 (B7 - S2)

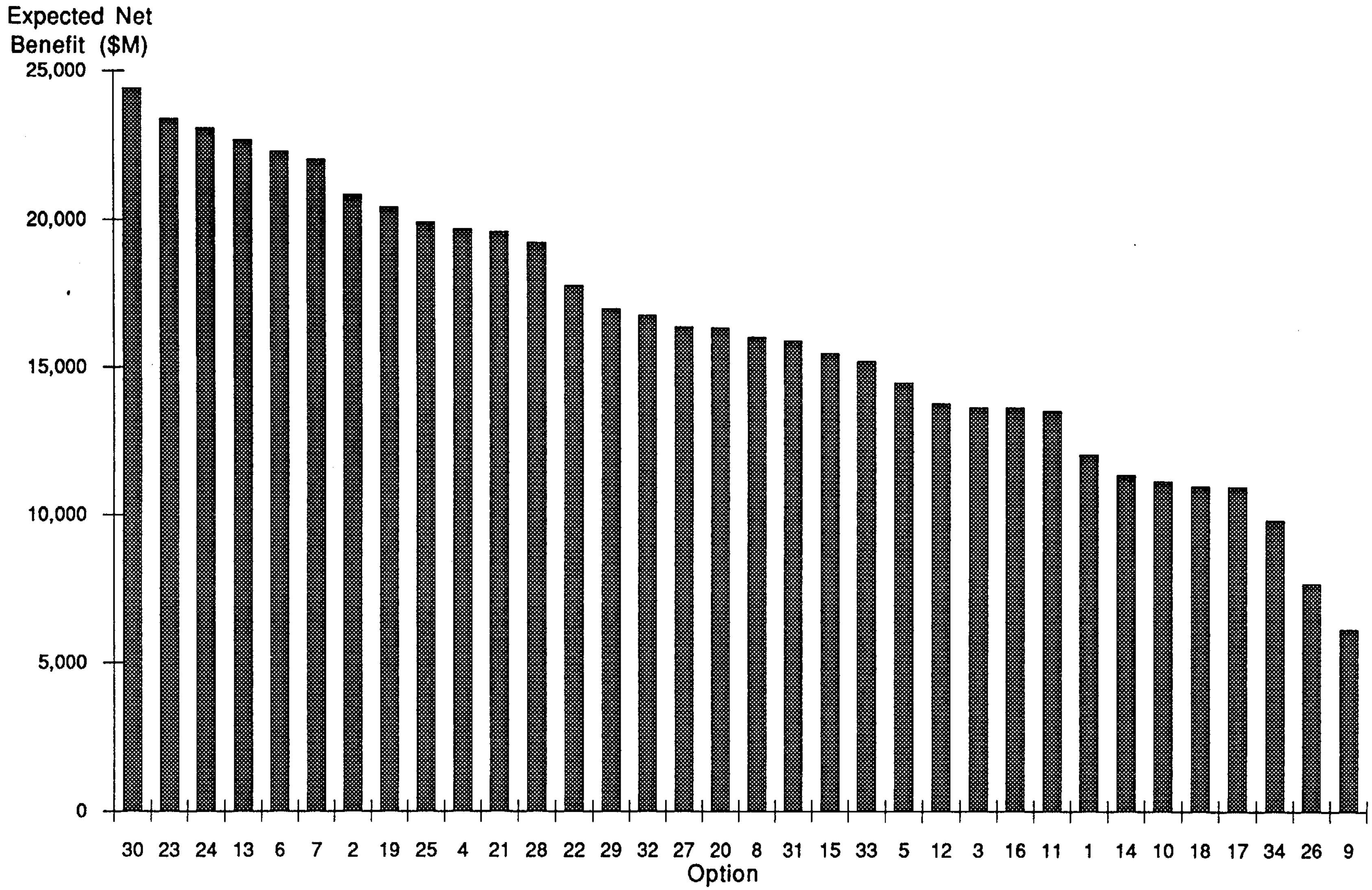

Figure 6-3. Expected Net Benefits Computed for Rank Order of 34 ESF-Repository Options

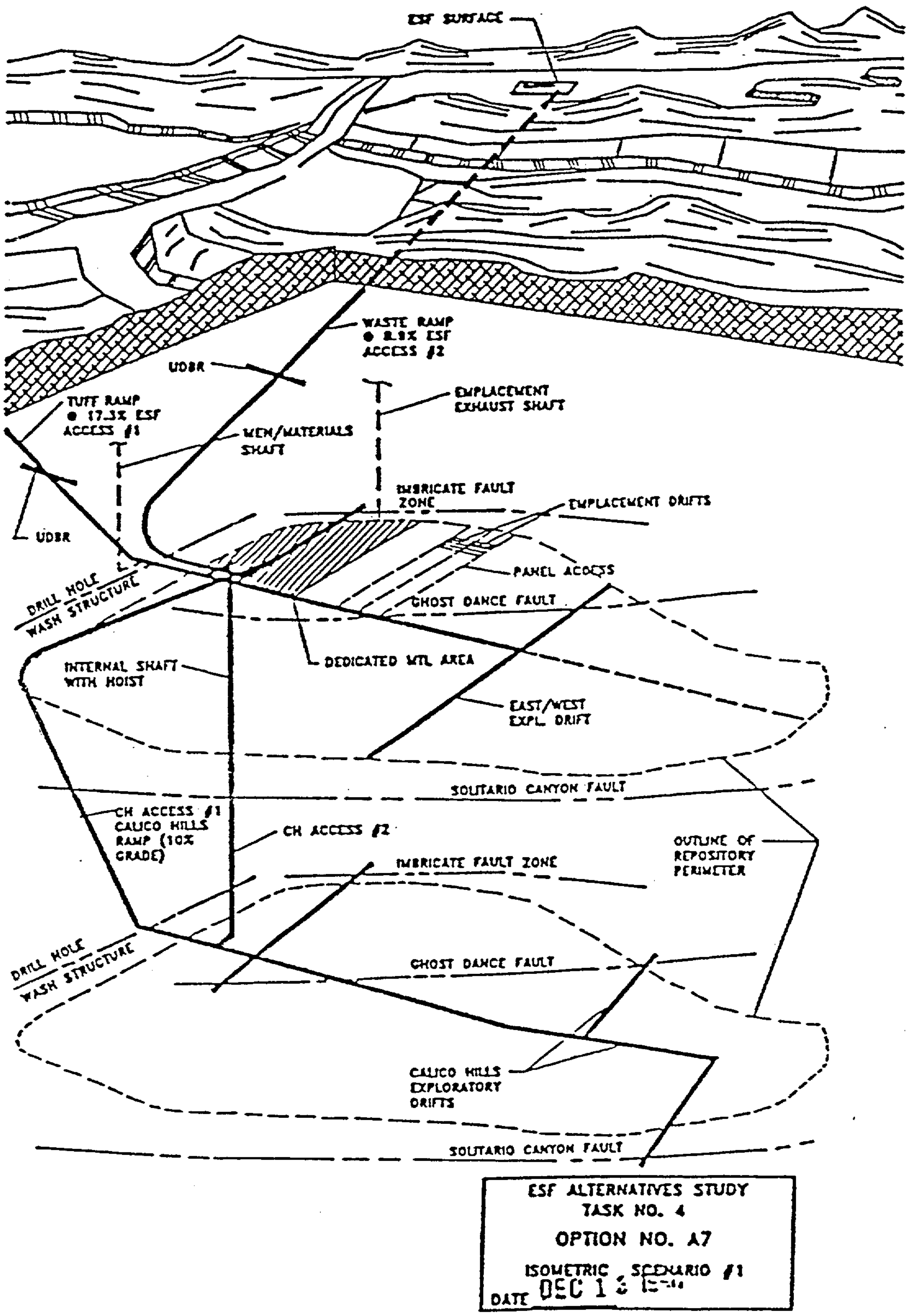

Figure 6-4. Underground Layout for Option 6 (A7)

this case both accesses would be from the north and the MTL would be located in the northeast corner of the repository block. The two additional repository accesses were 25-foot diameter shafts located, in this case, off the repository block.

Figure 6-5 shows the layout for Option Pair 7 and 24. The MTL and repository are mechanically mined, as in Option Pair 13 and 30. There are five accesses in total. In addition to a 25-foot diameter ramp from the northeast, the MTL would also be accessed by a 16-foot diameter mechanically mined shaft. The three additional repository accesses, all in the north, would consist of two 25-foot-diameter mechanically mined shafts (one off the repository) and a 25-foot-diameter TBM-driven tuff ramp from the north.

6.2 <u>Sensitivity of the Ranking to the Value of a Closed Repository</u>

Figure 6-6 illustrates how changes in the assumed benefit, *B*, of a closed repository affect the expected net benefits computed for several of the options. Not surprisingly, the expected net benefit increases as *B* increases. Note that if the value of *B* is low enough, the expected net benefits are negative. This demonstrates mathematically an intuitive result -- no option is worth selecting unless the benefits of a closed repository would be sufficiently high to outweigh the expected adverse consequences.

For sufficiently large values of *B* (around $12 billion or above), the ranking of the ESF options does not depend on *B*. For lower values of *B*, there are some shifts in ranking. Figure 6-7 illustrates these shifts and the values of *B* at which they occur.

6.3 <u>Dependence of the Ranking on the Probability of Obtaining a Closed Repository</u>

In Figure 6-8, the Scenario A probabilities for the various ESF options are shown superimposed over the bar chart showing the expected net benefits of the options. The figure demonstrates that the ranking of options based on expected net benefit was determined to be almost identical to that based on the probability of Scenario A. The ranking of an option is determined almost entirely by the estimated likelihood that the option would result in a closed repository. Option 30 had the highest estimated probability, 60 percent, of resulting in a closed repository. Because only this scenario produced a positive benefit, and because the options do not differ much in terms of the consequences for a given scenario, the analysis indicated that the best option would be the one that is most likely to lead to a closed repository.

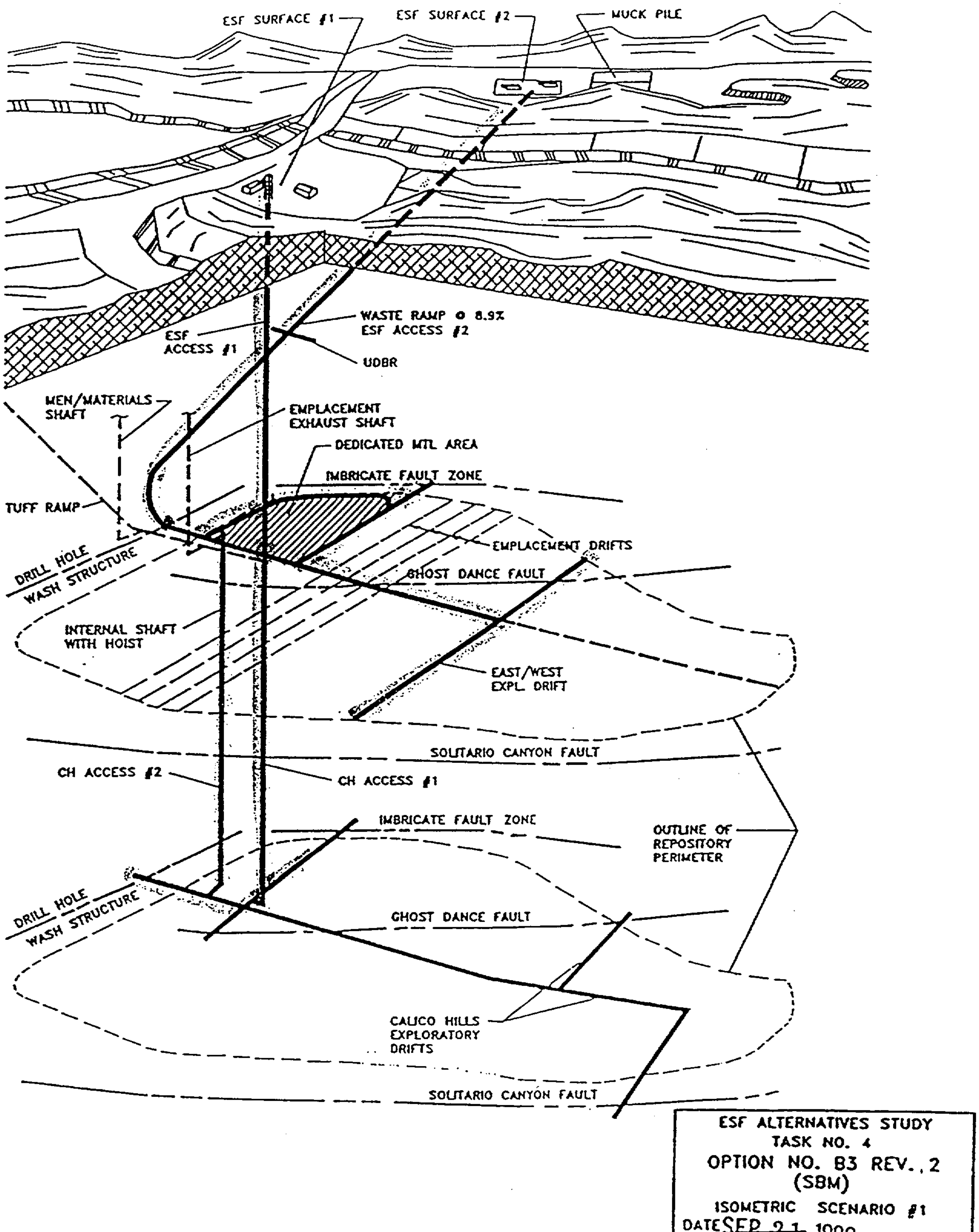

Figure 6-5. Underground Layout for Option 7

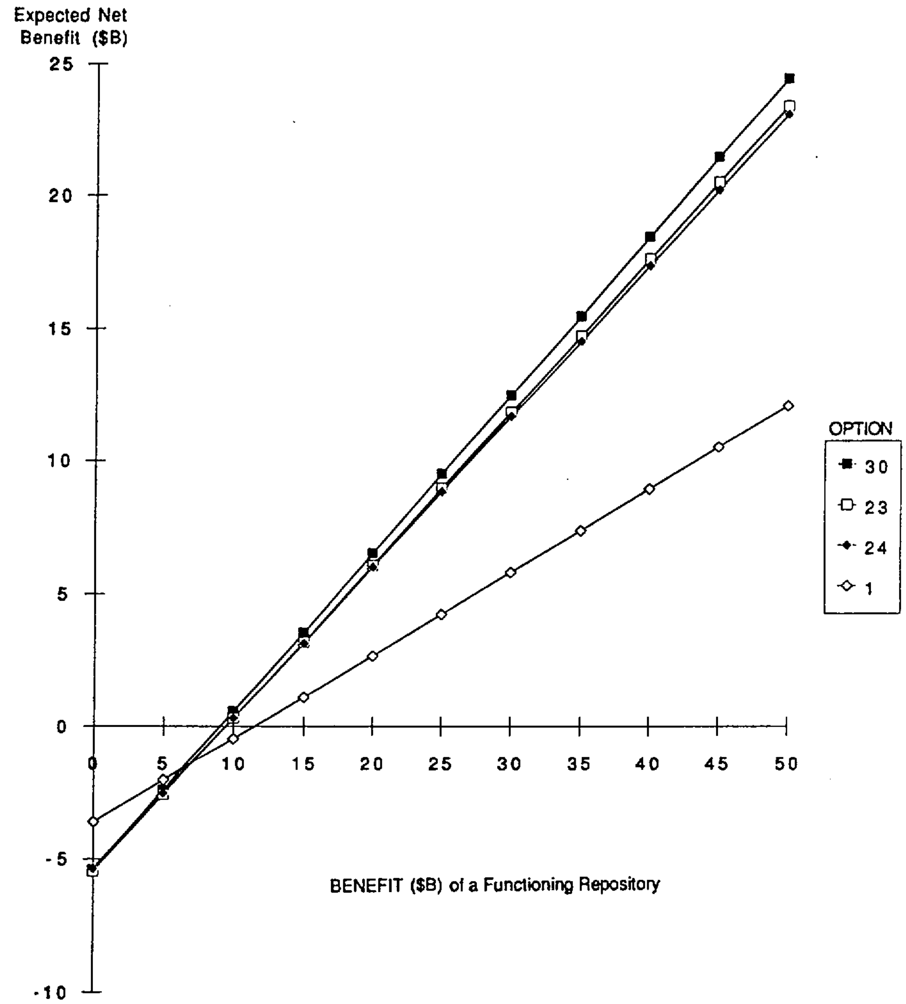

Figure 6-6. Sensitivity of Expected Net Benefit to the Benefit of a Functioning Repository

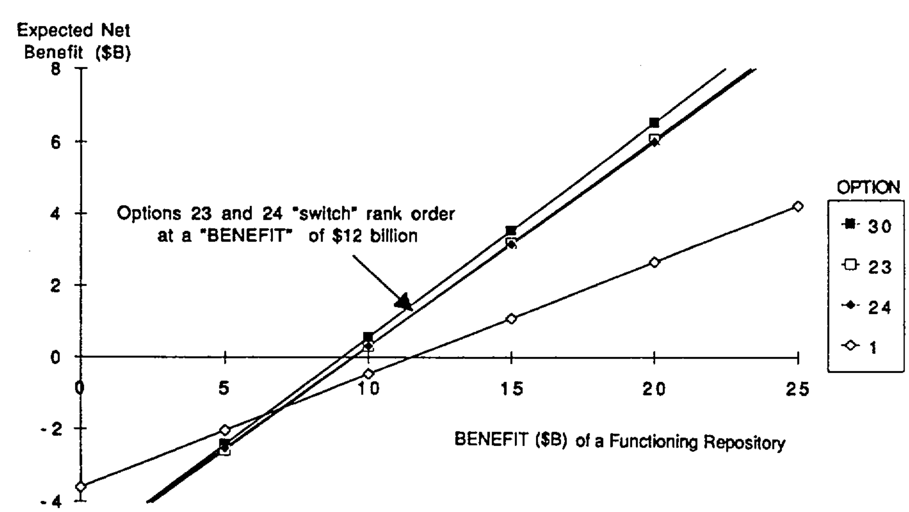

Figure 6-7. Sensitivity of Expected Net Benefit to the Benefit of a Functioning Repository

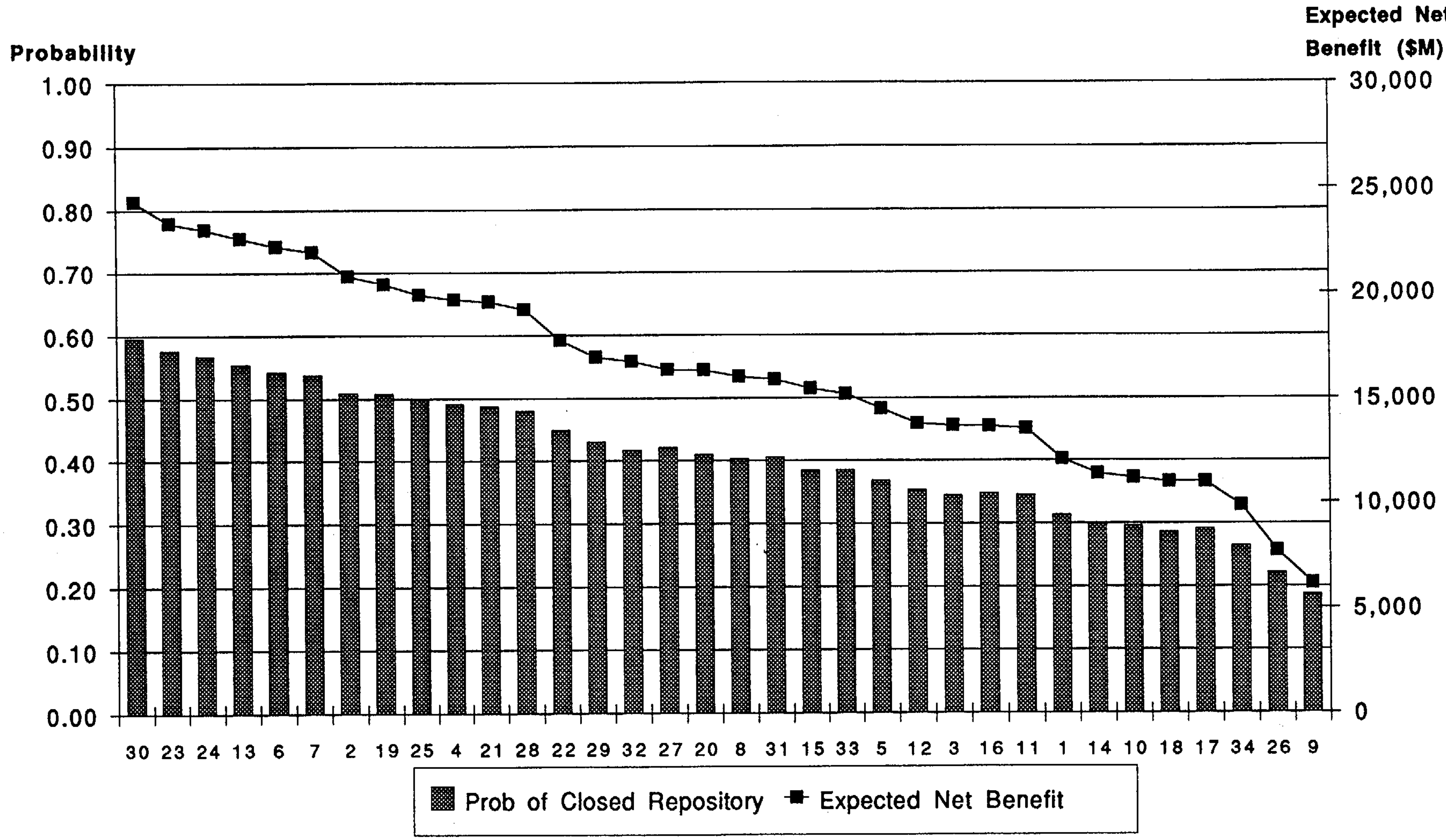

Figure 6-8. Scenario A Probabilities and Expected Net Benefits for 34 ESF-Repository Options

The issue of whether the computed probabilities of obtaining a closed repository are too low (i.e., in error) was an important one for the analysis. If the probability of obtaining a closed repository had been much higher (90 percent or more), then the consequence estimates would have had a much greater impact on the overall ranking. This means that the comparative evaluation results are correct only if the probability of obtaining a closed repository is indeed within the range estimated. If the probability of obtaining a closed repository is really much higher than 60 percent, then the rankings produced by the study would change significantly.

The probability of the closed repository scenario was computed as the product of the probabilities of each of five key events that must occur to obtain a closed repository: (1) near-term program viability, (2) "OK" results from early testing, (3) "OK" results from late testing, (4) regulatory approval to construct and operate the repository, and (5) a decision to close the repository rather than retrieve emplaced waste. The probabilities estimated by the various panels for these events ranged from less than 50 percent to 99.9 percent, depending on the event and the ESF option. The product of the probabilities and, therefore, the probability of obtaining a closed repository, ranged from 19 percent to 60 percent, depending on the option.

It can be argued that the estimated probability of success might be slightly low due to the assumption in the analysis that a "bad outcome" on any event (e.g., early tests indicating that the site is "NOT OK") would result in abandonment of the site. In fact, the site might not be abandoned in all such circumstances. For example, failure to obtain regulatory approval might result in additional testing and a redesign of the repository rather than abandonment. Therefore, the probability of ultimate success may be somewhat higher than the estimated value, due to the conservative assumption that bad outcomes would always lead to abandonment of the site.

In view of the above argument, significant effort was made to check the "reasonableness" of the estimated probability of a closed repository. An important step in decision analysis is to compare the results of the analysis with people's intuition. If there is a disagreement, then one of two things must happen: (1) there is an error in the analysis, and that error must be identified and corrected or (2) people's intuitions will change to agree with the result of the analysis. Panel members were often asked whether the results of intermediate probability calculations seemed reasonable.

Typically, their initial reaction was, "The computed probability seems too low." However, as the logic of the analysis was explored and panelists looked for possible errors, participants' responses changed to, "The answer the analysis is coming up with may make some people uncomfortable, but it is the right answer."

The result that the ranking of options was determined by the probability that the option would produce a closed repository helps explain a curious feature that is shown in Figure 6-7. For values of *B* below about $7 billion, the expected values of the options are negative and the ranking of options is approximately inverted. The reason for this is that, if the benefit of a closed repository is assumed to be insufficient to justify its adverse impacts, the best strategy would be to minimize the chance that the repository is developed. This confirms an observation made in Section 2 -- if the benefits of a repository do not justify its costs, the best option would be the one with the lowest probability of producing a closed repository!

Figure 6-9 clarifies the role of the probability of Scenario A (see Figure 2-1) in determining expected net benefit. The figure shows the cumulative probability distributions for net benefit for two options, Option 30 and the Option 1. The cumulative probability distribution quantifies uncertainty over the consequences of choosing an option. These probability distributions were obtained from the decision tree, which quantifies uncertainty over scenarios, and the low, best-judgment, and high consequence estimates provided by the expert panels, which quantify uncertainty over the consequences that would result from a given scenario.

With a cumulative probability distribution, the height of the curve above any dollar value X_o on the X axis gives the probability that the actual net benefit resulting from the option would be less than or equal to X_o. Thus, the possible net benefits resulting from Option 30 range from roughly -$12 billion to +$46 billion. The possible net benefits resulting from Option 1 range from roughly -$6 billion to +$46 billion. Option 30 could result in greater benefit losses than Option 1 because of the higher economic costs associated with Option 30 and the possibility that any site might have to be abandoned after retrieving waste.

The straight-line "plateaus" on the plots correspond to the discontinuity in net benefit that occurs depending on whether or not the repository is closed (i.e., whether Scenario A occurs). The height of the plateau for a given option corresponds to the probability that a closed repository would not be achieved (1 minus the probability of Scenario A).

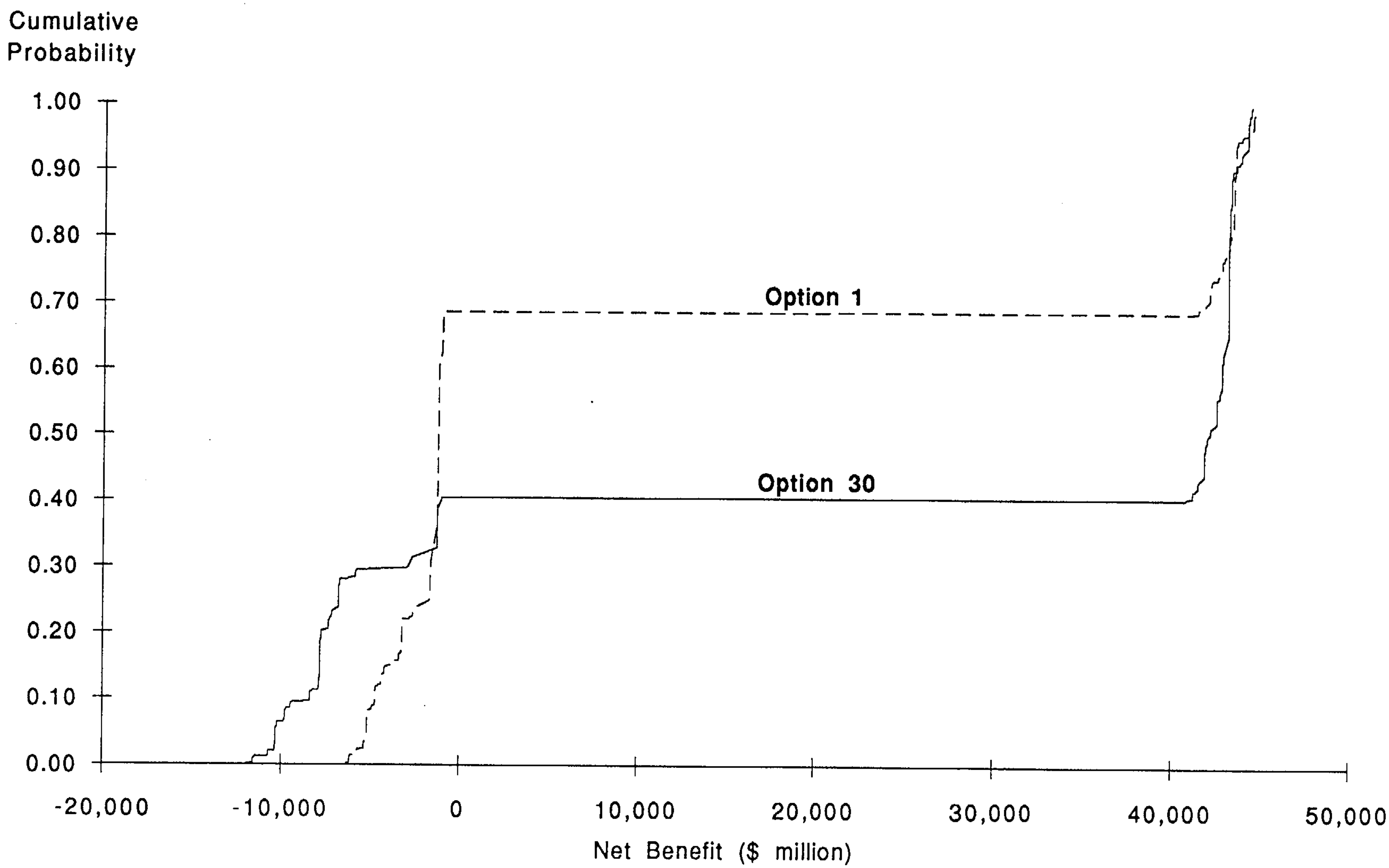

Figure 6-9. Probability Distributions on Net Benefit

Cumulative probability curves with higher plateaus have lower expected values. Thus, the probability of Scenario A was a major determinant of the expected value of the distribution, which was the measure that determined an option's relative ranking.

6.4 Specific Factors Influencing the Ranking

Table 6-2 shows the results of a correlation analysis designed to help clarify the specific assessments most influential in determining the option rankings. The analysis involved computing Spearman's rank correlation coefficient (Hays and Winkler, 1971), which was used to compare the overall ranking of the options with the rankings based on specific probability or consequence measures in the decision tree. According to the correlation coefficient, a number near +1 means the rankings produced by the two measures are nearly the same, a number near -1 means the rankings are nearly the inverse of one another, and a number near zero, means that there is no discernable relationship.

TABLE 6-2

CORRELATION BETWEEN OVERALL RANKING AND RANKINGS BASED ON SPECIFIC PERFORMANCE MEASURES

Discriminating Factors	Correlation Coefficient
Probability of Programmatic Viability	0.91
Probability of Regulatory Approval	0.63
Probability of Repository Closure	0.53
Radionuclide Releases to the Accessible Environment	0.51
Probability that Site is OK	0.40
Probability of an Early False Positive (P_{EFP})	0.38
Probability of a Late False Negative (P_{LFN})	0.32
Probability of an Early False Negative (P_{EFN})	0.31

The table lists those measures found to have the highest coefficients of correlation. High correlations suggest that the corresponding measures were important to the evaluation. As illustrated, highly ranked options are likely to have high programmatic viability, high probabilities of regulatory approval, high probabilities of closure, low radionuclide releases, high prior probability that the site is OK, and low probabilities of false negative test outcomes.

Figure 6-10 shows the results of a sensitivity analysis that provided similar conclusions. The analysis involved defining a hypothetical option with a score for each measure equal to the average score for the 34 ESF-repository options. The sensitivity analysis consisted of investigating how the expected net benefit of this hypothetical option would change as each performance measure is varied within a range defined by the lowest and highest levels specified for the 34 options. Once again, the sensitivity analysis shows the importance of programmatic viability, probability of regulatory approval, and testing probabilities (especially the probability of false negative outcomes).

Care must be taken in interpreting the correlation and sensitivity analyses, as both have limitations. A correlation shown in an analysis of this sort merely indicates that two measures tend to be statistically related. High correlations do not necessarily imply a cause-and-effect relationship. The sensitivity analysis shown in Figure 6-10 specifically accounted for the functional relationship between a measure and expected net benefit, but the sensitivity analysis fails to account for dependencies among the measures.

Several such dependencies exist among the performance measures because the measures assessed by some panels depended, in part, on the measures provided by other panels. For example, the sensitivity of expected net benefit to releases, shown in Figure 6-10, accounts for the effect of estimated releases on consequences of scenarios, but not for the effect of changing releases on the probability of regulatory approval. The probability of regulatory approval depended on estimated releases (specifically, the aqueous component of releases as indicated by the relevant influence diagram (Appendix B)). Accounting for this dependency in the sensitivity study would have required reconvening the panels that considered measures provided by other panels as input and asking them to provide revised estimates based on different assumptions for the input measures. Because this was not done, sensitivity analysis results to those measures that were considered as inputs for the assessment of other measures were underestimated. In addition to releases, these measures included the residual probability that the site is NOT OK (a function of the testing measures and P_{OK}) and the environmental impact measures.

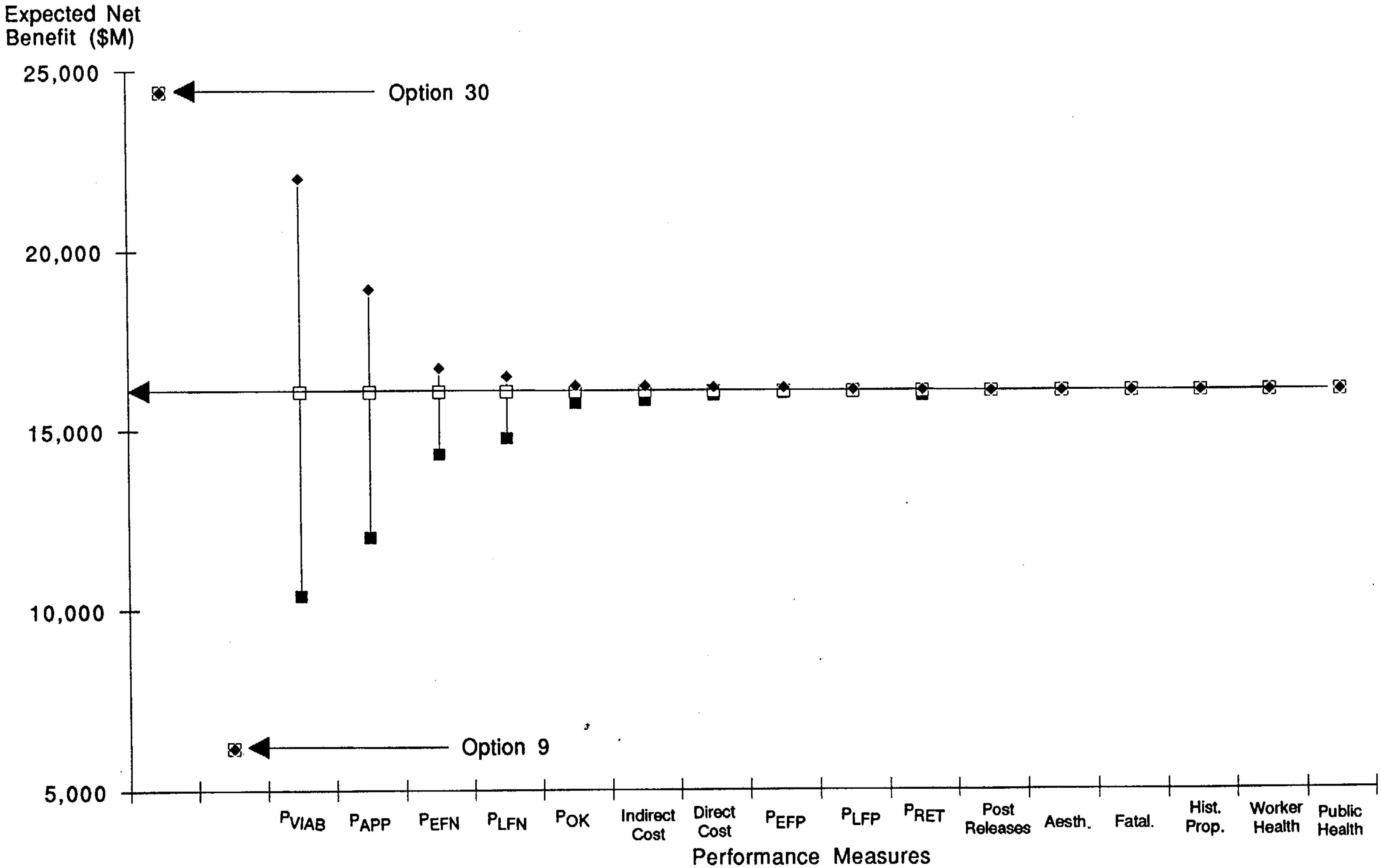

Figure 6-10. Sensitivity to All Performance Measures on an "Average" Option

Despite these limitations, Table 6-2 and Figure 6-10 clearly show that programmatic viability assessments were important to the overall ranking results. The explanation for the importance of programmatic viability estimates is provided by Table 6-3, which shows the individual probabilities in the decision tree whose product determined the probability of Scenario A. The probability estimates for programmatic viability varied from option to option far more than the probability estimates for the other uncertainties. In fact, programmatic viability was estimated to be twice as likely for Option 24 (90 percent) than for Option 9 (45 percent). This variation dominated the smaller variations across options estimated for the other uncertainties. Thus, programmatic viability was the most significant factor influencing the overall evaluation, and the ranking with respect to programmatic viability was, therefore, most highly correlated with the overall ranking.

Table 6-4 shows the correlation obtained by comparing the ranking based on probabilities of programmatic viability with the rankings based only on specific factors considered as part of the programmatic viability assessment. The results suggest that the extent to which an option was estimated to address NWTRB concerns was the single, most important factor in determining programmatic viability, which, in turn, was the single most important factor in determining the overall ranking. These concerns, which were technical in nature, evolved during a series of meetings between the DOE and the NWTRB. Other factors for which the correlation was relatively high included the extent to which the option was estimated to address NRC concerns and the date on which late testing would end. These factors were identified by the programmatic viability panel as being key influencing factors, as shown on the programmatic viability influence diagram (Section 3, Figure 3-2).

6.5 Option Rankings Based on Minority Reports

In a few cases, as explained in Sections 3 and 4, complete consensus on probabilities or consequence estimates was not reached by an expert panel. When this happened, the majority consensus (the consensus estimates agreed to by the majority of panel members) was used for the nominal analysis. However, minority reports were obtained to document the views of those panel members who could not agree with the majority. These minority reports were then used in sensitivity analyses.

TABLE 6-3

DECISION TREE PROBABILITIES

Option	Programmatic Viability (P_{VIAB})		"OK" Results From Early Testing ($P_{"OK-ET"}$)		"OK" Results From Late Testing ($P_{"OK-LT"}$)		Regulatory Approval P_{APP}		Repository Closure P_{CLO}		Scenario A Probability	
1	0.55	26th	0.83	18th	0.89	30th	0.78	24th	0.995	30th	0.31	27th
2	0.73	15th	0.83	11th	0.91	2nd	0.93	4th	0.998	11th	0.51	7th
3	0.52	31st	0.83	13th	0.90	5th	0.89	9th	0.998	17th	0.35	26th
4	0.74	13th	0.83	16th	**0.92**	**1st**	0.87	12th	0.999	4th	0.49	10th
5	0.58	21st	0.84	9th	0.90	8th	0.85	15th	0.999	7th	0.37	22nd
6	0.78	9th	0.83	15th	0.90	17th	0.93	3rd	0.999	3rd	0.54	5th
7	0.79	7th	0.82	25th	0.90	9th	0.92	5th	0.998	13th	0.54	6th
8	0.64	18th	0.83	24th	0.90	18th	0.85	15th	0.998	15th	0.40	19th
9	0.45	34th	0.74	33rd	0.84	33rd	0.67	33rd	0.991	34th	0.19	34th
10	0.58	22nd	0.78	32nd	0.89	24th	0.74	29th	0.996	28th	0.30	29th
11	0.56	24th	0.82	26th	0.90	6th	0.83	18th	0.997	23rd	0.35	25th
12	0.58	23rd	0.84	5th	0.90	11th	0.81	21st	0.998	8th	0.35	23rd
13	0.81	6th	**0.85**	**1st**	0.91	3rd	0.89	9th	**0.999**	**1st**	0.55	4th
14	0.51	33rd	0.84	8th	0.90	7th	0.78	25th	0.998	12th	0.30	28th
15	0.54	28th	0.83	20th	0.90	10th	**0.95**	**1st**	0.999	5th	0.38	21st
16	0.53	29th	0.81	29th	0.89	23rd	0.90	7th	0.999	2nd	0.35	24th
17	0.56	25th	0.83	21st	0.90	13th	0.70	31st	0.997	25th	0.29	30th
18	0.52	32nd	0.82	28th	0.88	32nd	0.77	27th	0.995	31st	0.29	31st
19	0.77	10th	0.83	12th	0.89	26th	0.90	8th	0.997	18th	0.51	8th
20	0.67	17th	0.83	17th	0.89	27th	0.83	18th	0.997	21st	0.41	17th
21	0.77	12th	0.84	3rd	0.90	12th	0.84	17th	0.998	16th	0.49	11th
22	0.77	11th	0.84	4th	0.90	20th	0.78	25th	0.997	22nd	0.45	13th
23	0.87	3rd	0.83	14th	0.89	28th	0.90	6th	0.998	10th	0.58	2nd
24	**0.90**	**1st**	0.82	27th	0.89	25th	0.86	14th	0.997	24th	0.57	3rd
25	0.84	4th	0.83	23rd	0.90	16th	0.80	22nd	0.997	19th	0.50	9th
26	0.55	27th	0.74	34th	0.83	34th	0.66	34th	0.991	33rd	0.22	33rd
27	0.83	5th	0.79	31st	0.89	31st	0.73	30th	0.996	29th	0.42	15th
28	0.79	8th	0.83	22nd	0.90	14th	0.82	20th	0.997	26th	0.48	12th
29	0.73	14th	0.84	7th	0.90	15th	0.79	23rd	0.997	20th	0.43	14th
30	0.89	2nd	0.85	2nd	0.91	4th	0.87	13th	0.999	6th	**0.60**	**1st**
31	0.70	16th	0.84	6th	0.90	21st	0.77	28th	0.997	27th	0.41	18th
32	0.62	19th	0.80	30th	0.90	19th	0.94	2nd	0.998	9th	0.42	16th
33	0.59	20th	0.83	19th	0.90	22nd	0.88	11th	0.998	14th	0.39	20th
34	0.53	30th	0.83	10th	0.89	29th	0.69	32nd	0.995	32nd	0.26	32nd

TABLE 6-4

CORRELATION BETWEEN RANKINGS FROM PROBABILITY ESTIMATES AND DISCRIMINATING FACTORS FOR PROGRAMMATIC VIABILITY

Discriminating Factors	Correlation Coefficient
Resolution of NWTRB Concerns	0.63
Resolution of NRC Concerns	0.49
End-date of Late Testing (LA Target Date)	0.40
Probability of Repository Construction/Operation Approval	0.32
End-date of Early Testing	0.28
Schedule Difference Between End Dates of Early Testing and Early Drifting	0.22
Schedule Slippage Because of ESF Redesign Requirements	0.07
Design Dissimilarity With Base-Case ESF	0.03
Residual Probability that the Site is NOT OK, given Early/Late Testing Indicates that it is "OK"	0.02
Total ESF Costs to End of Late Testing	-0.16
Average ESF Cost per Month	-0.33

Table 6-5 summarizes the minority reports and their impact on the rankings. The first column shows the nominal ranking based on majority reports. The other columns show the rankings produced when the probabilities or consequences in the tree are changed to reflect those specified in minority reports. By far, the minority report having the biggest impact on rankings was the alternative set of programmatic viability probability estimates provided by the dissenting member of the programmatic viability panel. As explained in Section 4, this individual, unlike the other panel members, assigned a probability of one to many of the options, indicating his belief that many of the options posed essentially no risk of loss of programmatic viability. In addition, this individual assigned more emphasis to the influence of early delays on programmatic viability and

TABLE 6-5

RANK ORDER OF OPTIONS UNDER VARIOUS MAJORITY/MINORITY REPORTS

Majority Best Judgment Ranking		Minority View of Programmatic Viability		Minority EFN View #1 (7 experts)		Minority EFN View #2 (2 experts)		Minority View on Retrieval {NO CHANGE}		Ranking Without C14 Releases {NO CHANGE}		Revised Estimates of Testing Probabilities (EFN, EFP)	
30	1st	13	1st	30	1st	23	1st	30	1st	30	1st	30	1st
23	2nd	2	2nd	23	2nd	24	2nd	23	2nd	23	2nd	23	2nd
24	3rd	6	3rd	13	3rd	6	3rd	24	3rd	24	3rd	24	3rd
13	4th	23	4th	24	4th	30	4th	13	4th	13	4th	13	4th
6	5th	19	5th	6	5th	7	5th	6	5th	6	5th	6	5th
7	6th	4	6th	7	6th	13	6th	7	6th	7	6th	7	6th
2	7th	7	7th	2	7th	2	7th	2	7th	2	7th	2	7th
19	8th	5	8th	19	8th	19	8th	19	8th	19	8th	19	8th
25	9th	21	9th	4	9th	25	9th	25	9th	25	9th	4	9th
4	10th	24	10th	25	10th	28	10th	4	10th	4	10th	25	10th
21	11th	15	11th	21	11th	21	11th	21	11th	21	11th	21	11th
28	12th	12	12th	28	12th	32	12th	28	12th	28	12th	28	12th
22	13th	3	13th	22	13th	27	13th	22	13th	22	13th	22	13th
29	14th	20	14th	29	14th	4	14th	29	14th	29	14th	29	14th
32	15th	29	15th	32	15th	20	15th	32	15th	32	15th	32	15th
27	16th	32	16th	31	16th	22	16th	27	16th	27	16th	27	16th
20	17th	14	17th	20	17th	29	17th	20	17th	20	17th	20	17th
8	18th	22	18th	27	18th	8	18th	8	18th	8	18th	8	18th
31	19th	28	19th	8	19th	15	19th	31	19th	31	19th	31	19th
15	20th	31	20th	15	20th	33	20th	15	20th	15	20th	33	20th
33	21st	30	21st	33	21st	31	21st	33	21st	33	21st	15	21st
5	22nd	8	22nd	5	22nd	16	22nd	5	22nd	5	22nd	5	22nd
12	23rd	25	23rd	12	23rd	5	23rd	12	23rd	12	23rd	16	23rd
3	24th	11	24th	3	24th	11	24th	3	24th	3	24th	12	24th
16	25th	16	25th	11	25th	1	25th	16	25th	16	25th	3	25th
11	26th	33	26th	16	26th	12	26th	11	26th	11	26th	11	26th
1	27th	18	27th	1	27th	3	27th	1	27th	1	27th	1	27th
14	28th	1	28th	14	28th	10	28th	14	28th	14	28th	14	28th
10	29th	17	29th	17	29th	18	29th	10	29th	10	29th	10	29th
18	30th	10	30th	10	30th	17	30th	18	30th	18	30th	18	30th
17	31st	27	31st	18	31st	14	31st	17	31st	17	31st	17	31st
34	32nd	34	32nd	34	32nd	34	32nd	34	32nd	34	32nd	34	32nd
26	33rd	9	33rd	26	33rd	26	33rd	26	33rd	26	33rd	26	33rd
9	34th	26	34th	9	34th	9	34th	9	34th	9	34th	9	34th

less influence to other factors considered by the panel. As shown, the ranking under this different view was substantially different from that produced when the majority view of the other six panel members was used.

Compared to the large change in rankings obtained using the minority report on programmatic viability, the other minority reports produced little or no changes to the rankings. As indicated in Table 6-5, Option 30 was at the top in all cases but one, and in this case, Option 23, the option ranked second in the nominal ranking, came out at the top.

6.6 Additional Sensitivity Analyses

Sensitivity analyses consisted of varying the inputs to the decision tree across the ranges established by the high and low estimates provided by the expert or management panels. Figure 6-11 shows the results for the most sensitive of all the inputs, the estimated probabilities of programmatic viability. The open squares show the expected net benefit computed for each option under the nominal analysis. The solid squares and diamonds show how the computed expected net benefits changed for each option when different probabilities of programmatic viability were assumed. Specifically, the bars show 95 percent confidence bands for uncertainties related to programmatic viability -- the extreme values were computed using the 95 percent confidence estimates for the probability of programmatic viability.

The confidence bands are wider for some options than for others. This reflects the judgment by the programmatic viability panel that the uncertainties regarding the estimation of programmatic viability were greater for some options than for others. The fact that the bars in Figure 6-11 overlap indicates that it is possible for the ranking of options to be quite different than that indicated by the nominal analysis. For example, it is possible for the lowest-ranked option to actually be superior to the best-ranked option. However, this is unlikely, because of dependencies in the uncertainties regarding programmatic viability. In other words, if the panel vastly underestimated the probability of programmatic viability for Option 9, then it would be likely that the probability was also underestimated for Option 30. It would have been very unlikely that the probability would be underestimated for Option 9 but overestimated for Option 30. Even so, the fact that the results were highly sensitive to programmatic viability probability estimates, and the uncertainties in these estimates as determined by the expert panel, is clearly indicated by Figure 6-11.

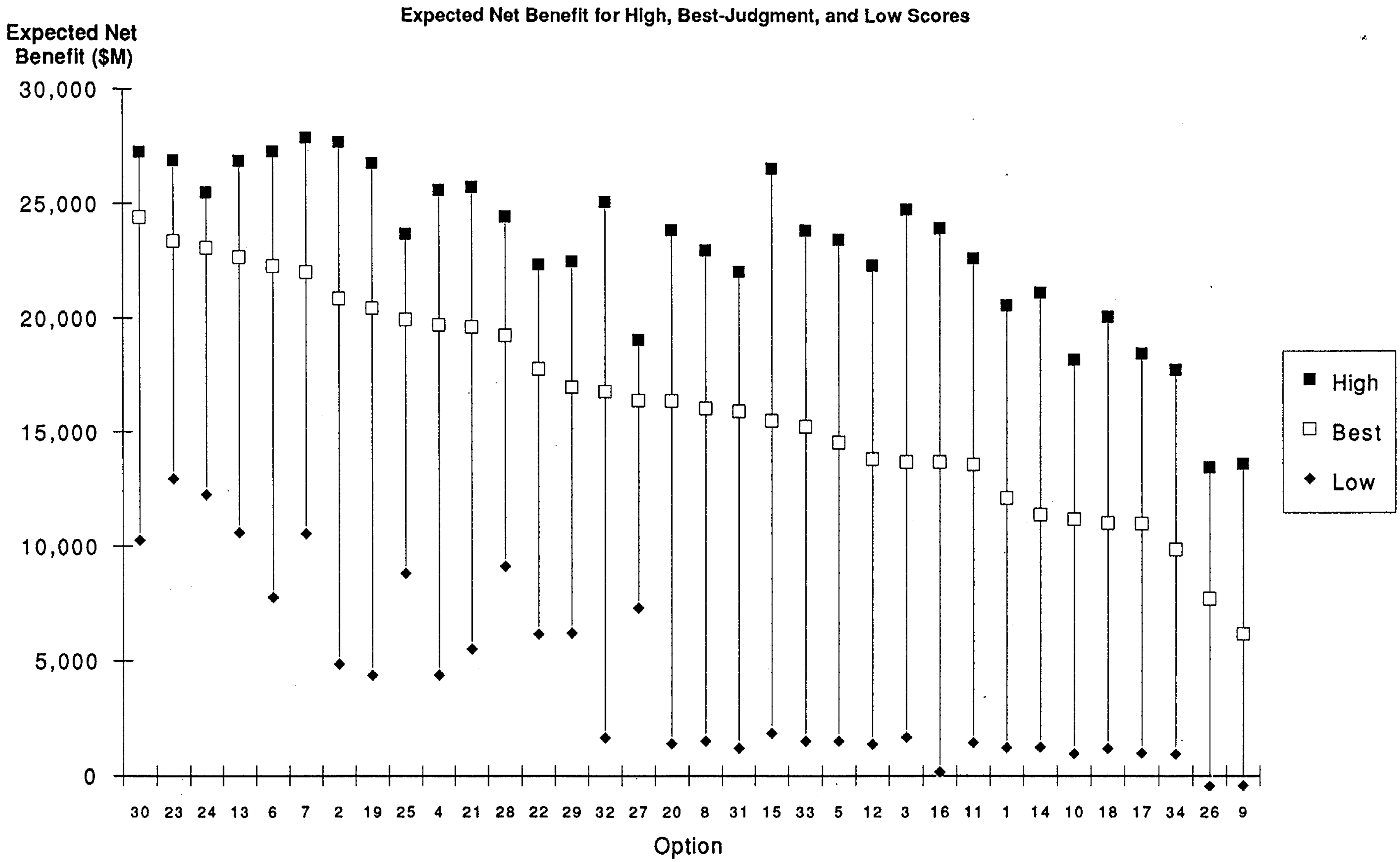

Figure 6-11. Sensitivity Analysis on Probability of Program Viability

The other sensitivity analysis results were similar, if less dramatic. Figure 6-12 shows the sensitivity of expected net benefits to the second most sensitive measure -- estimates of the probability of regulatory approval. Again, some options were estimated to be more uncertain than others, as indicated by the varying length of the confidence bars.

Figures 6-13 through 6-15 show other sensitivity results. Figure 6-13 shows the sensitivity to probability of closure. Figure 6-14 shows the sensitivity to discounted indirect costs. Indirect costs were the most sensitive of the consequences estimates. Figure 6-15 shows the sensitivity to direct costs.

Figure 6-16 shows a partial sensitivity analysis to release estimates. The plot shows the effect of changing the postclosure release estimates assumed in computing the net benefit of the scenarios in the decision tree. The analysis is termed "partial " because, as explained above, it accounts for the effect of estimated releases on consequences of scenarios, but not on the probability of scenarios. The probability of scenarios depended on release estimates because the probability of regulatory approval depended on the aqueous component of releases.

Figure 6-17 shows the sensitivity to changes in the scaling factor assumed for postclosure releases. To obtain this plot, the scaling factor was varied between the high and low values as specified by the Management Panel (see Table 5-5). Since the consequence estimates for releases had little effect on the ranking, compared to the effect of probability estimates, changes in the scaling factor also had little effect. Similar plots were developed for the other scaling factors. In all cases, variations across the ranges specified by the Management Panel produced only very minor changes to rankings.

Figure 6-18 shows the sensitivity to the discount rate. The discount rate reflects the preference for avoiding high near-term costs. It is interesting to note that the net benefit estimates for the highly ranked options were much more sensitive to the discount rate (particularly a lower rate) than were the lower ranked options. This result might appear to suggest that the higher ranked options have higher costs in the more distant future. Actually, the reason is that the higher ranked options have a higher probability of being licensed, meaning that they have a higher likelihood of producing future costs of any kind.

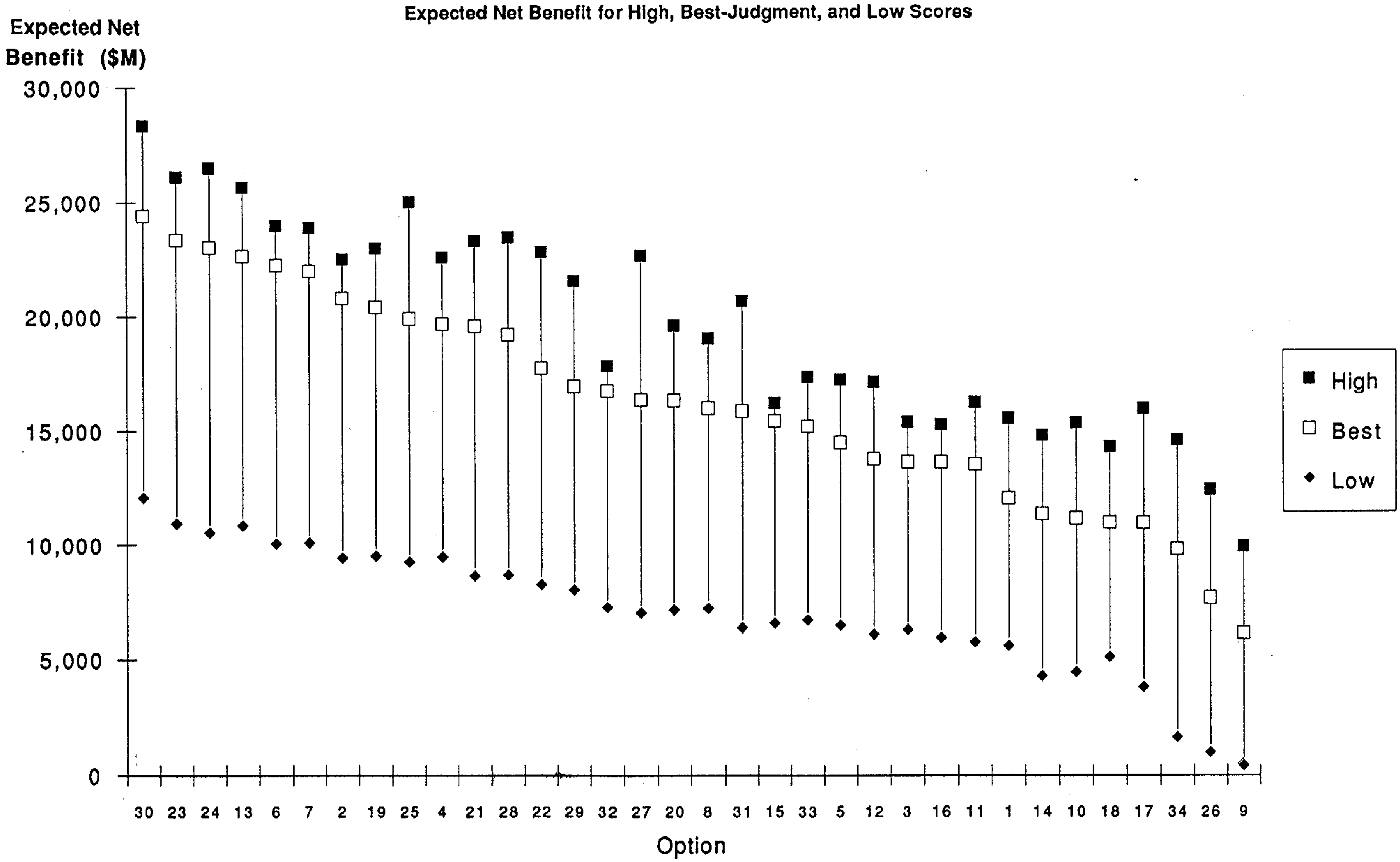

Figure 6-12. Sensitivity Analysis on Probability of Regulatory Approval

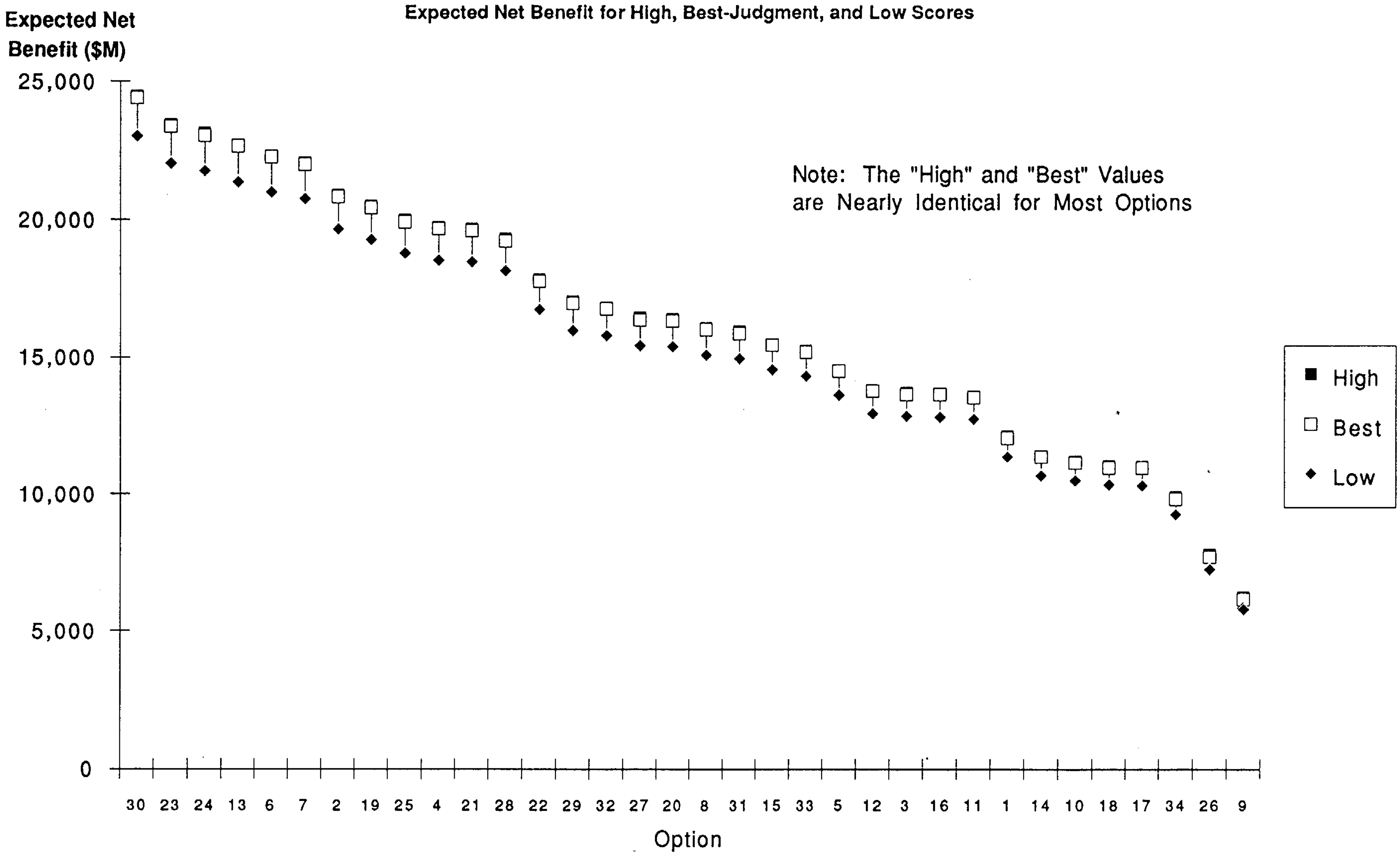

Figure 6-13. Sensitivity Analysis on Probability of Closure

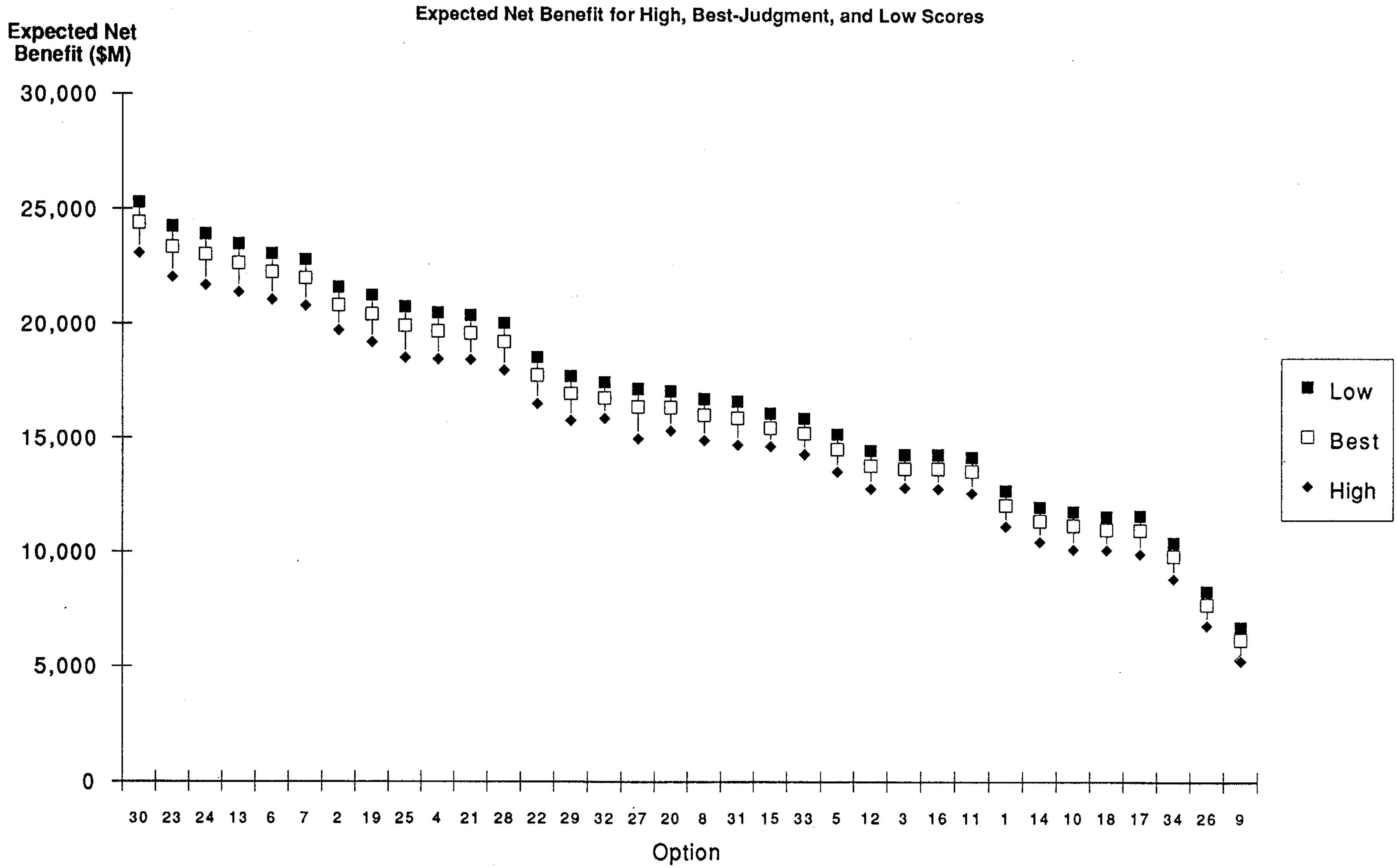

Figure 6-14. Sensitivity Analysis on Discounted Indirect Costs

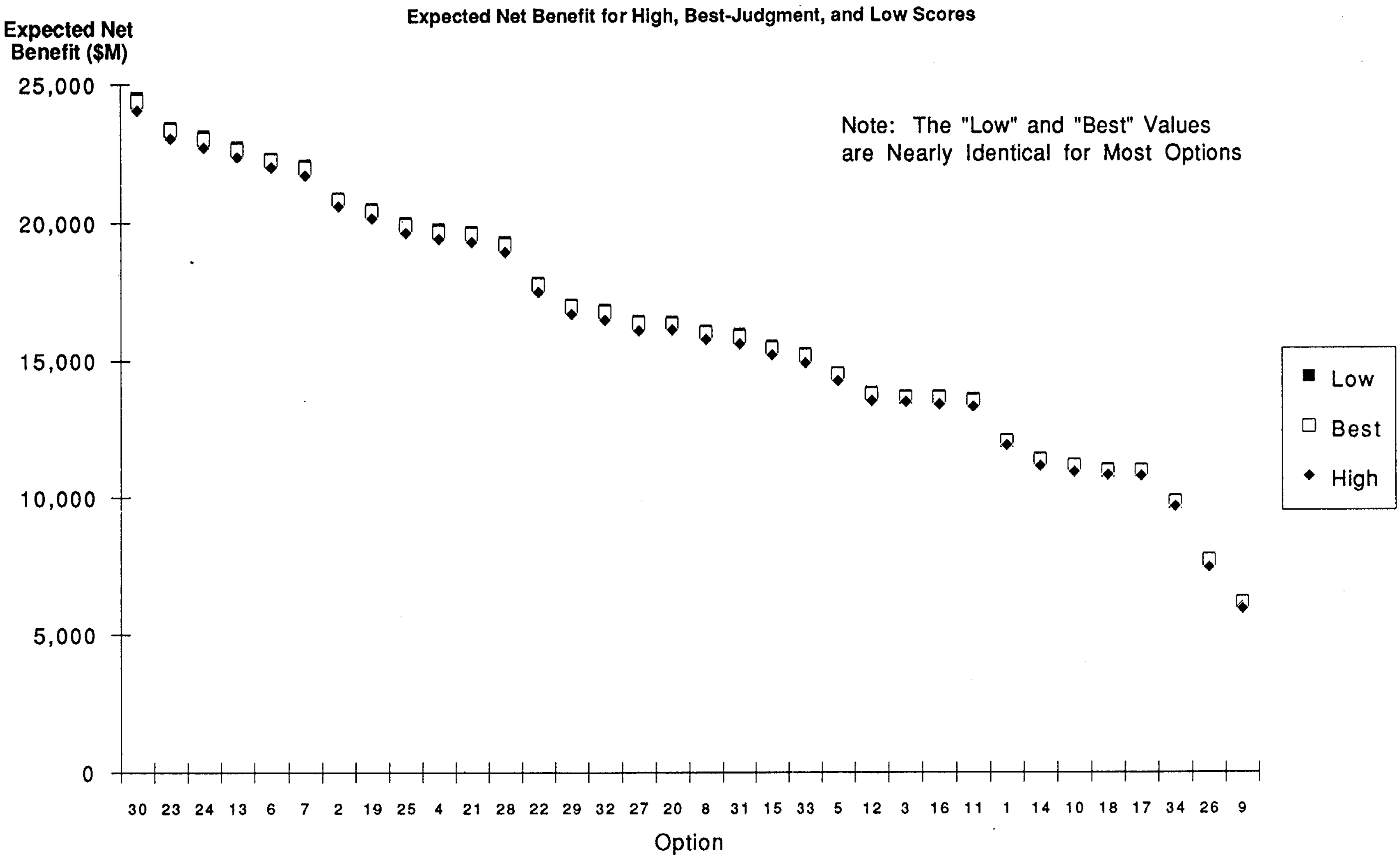

Figure 6-15. Sensitivity Analysis on Discounted Direct Costs

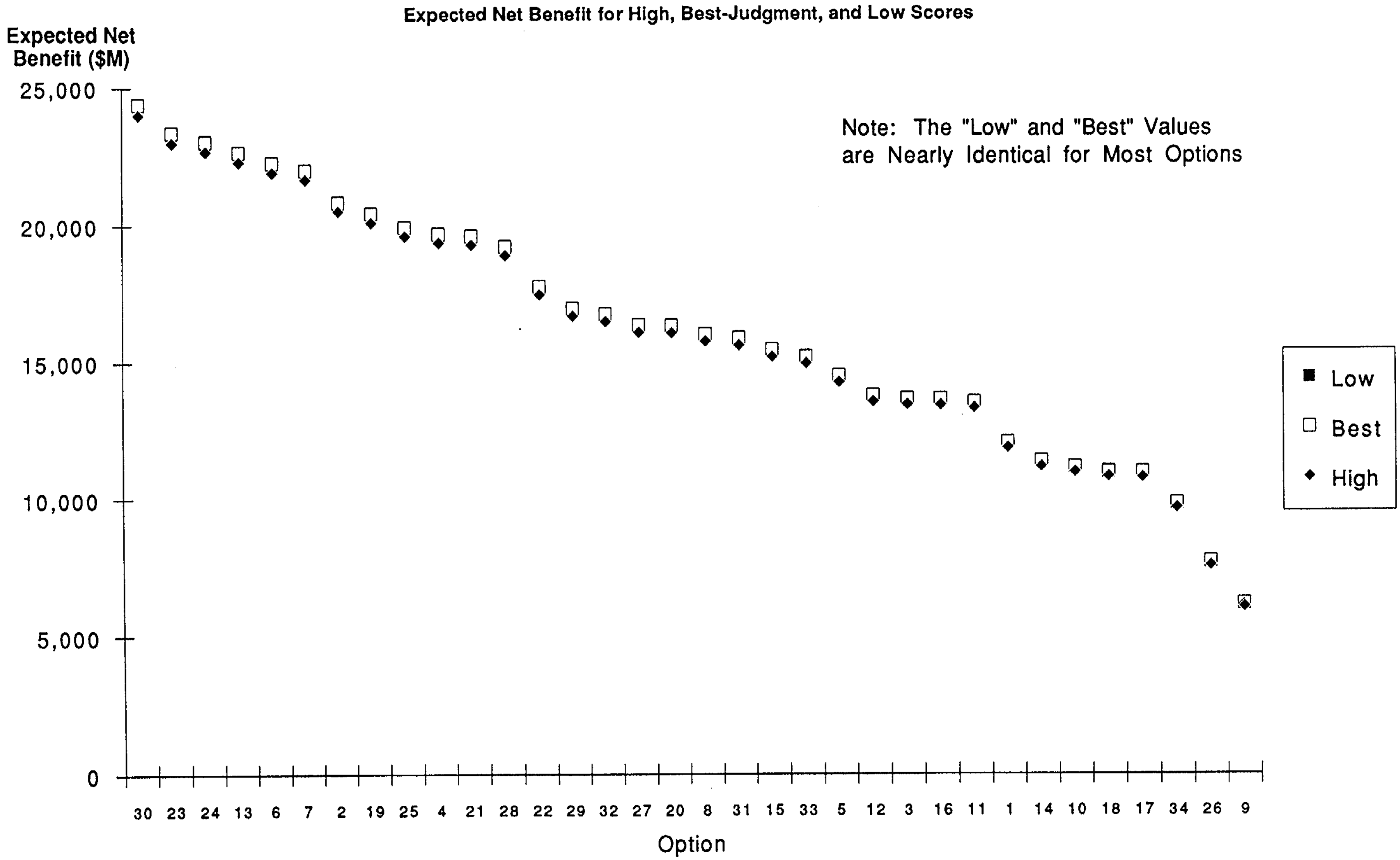

Figure 6-16. Sensitivity Analysis on Postclosure Releases

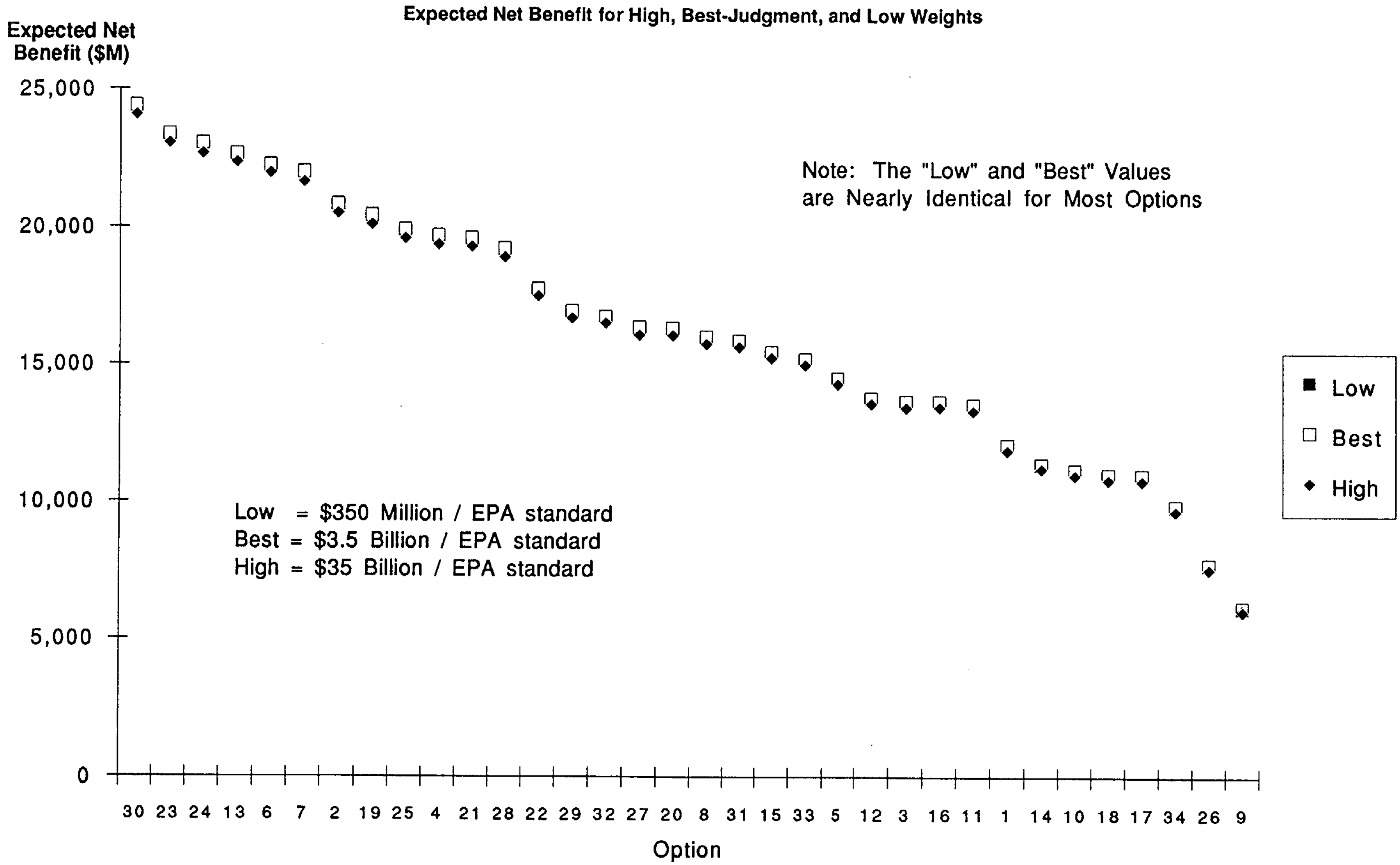

Figure 6-17. Sensitivity to Scaling Factor for Postclosure Releases

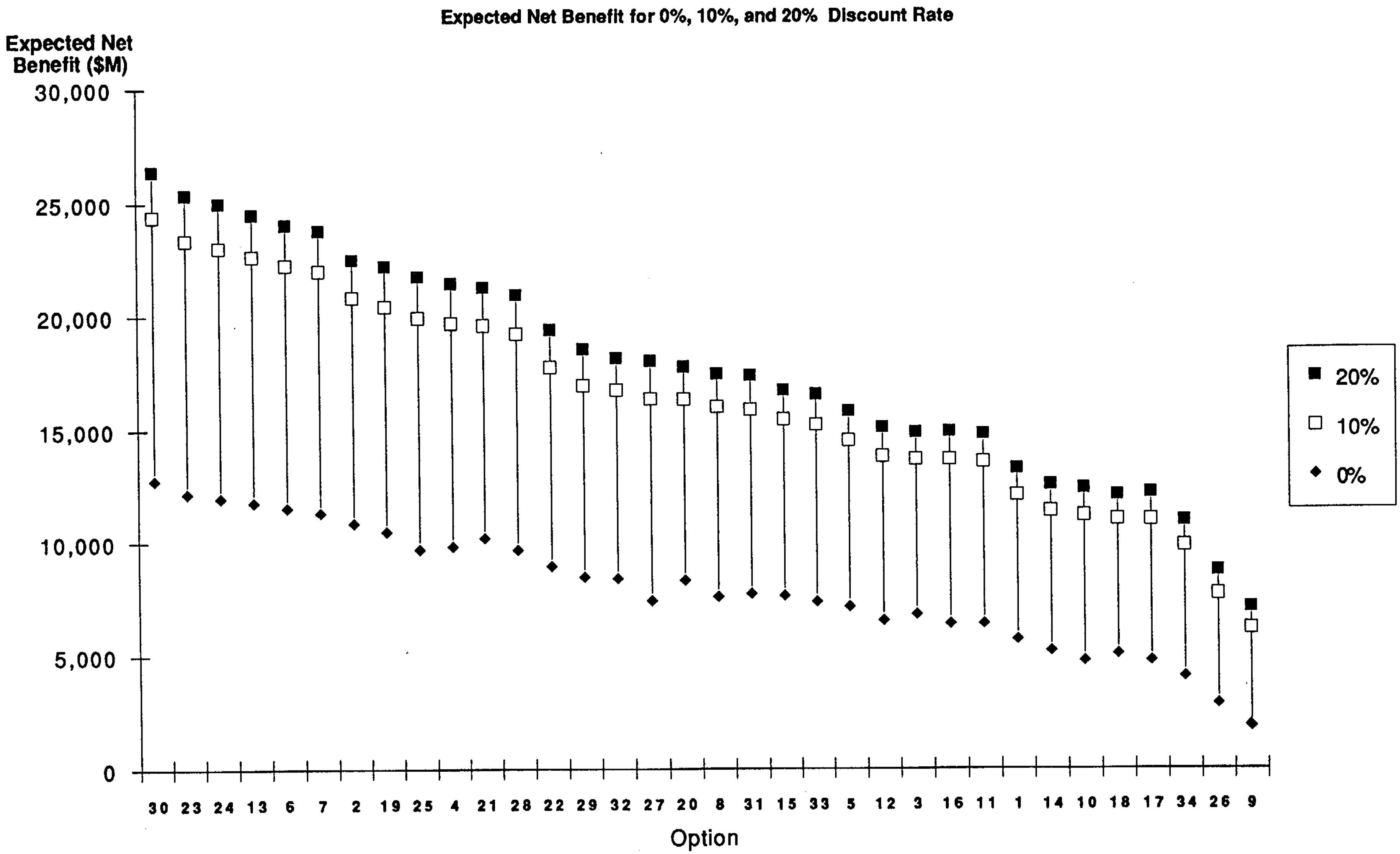

Figure 6-18. Sensitivity to Cost Discount Rate

Figure 6-19 shows the sensitivity of the evaluations of net benefit to alternative attitudes towards risk taking. As explained in Section 5, the utility function in Equation 5-1 reflects a neutral attitude to risk taking. Equation 5-3 allows risk-averse attitudes to be considered. Figure 6-19 shows the equivalent net benefit (called the certainty equivalent) obtained using the alternative utility function of Equation 5-3. The plot shows the computed net benefit for several options as a function of risk tolerance, which is a measure of the degree of aversion to risk. As illustrated, if risk tolerance is low enough (i.e., if the aversion to risk taking is high enough), the net benefits of the options would be negative. This suggests that decision makers who are extremely risk-averse would not like any of the options, because all offered some chance of adverse outcomes.

Table 6-6 shows the effect on the rankings of assuming three alternative risk attitudes (labeled risk neutrality, low risk aversion, and high risk aversion). As illustrated, the rankings were not very sensitive to changes in risk attitude, assuming sufficient risk tolerance to justify proceeding with at least one option.

Numerous other sensitivity analyses were also conducted. In all these additional analyses, changes in assumptions were found not to significantly change the overall rankings of options. For example, it might be argued that Scenario B in the decision tree, which results in retrieval of waste, offers some benefit relative to Scenarios C, D, E, and F, which result in abandonment of the site, with waste left at the reactors. To reflect a view that retrieved waste at Yucca Mountain would be preferable to waste at reactors, the decision tree was evaluated assuming that a benefit *B*' would result under Scenario B. For values of *B*' between zero and $10 billion, no change in rankings was produced.

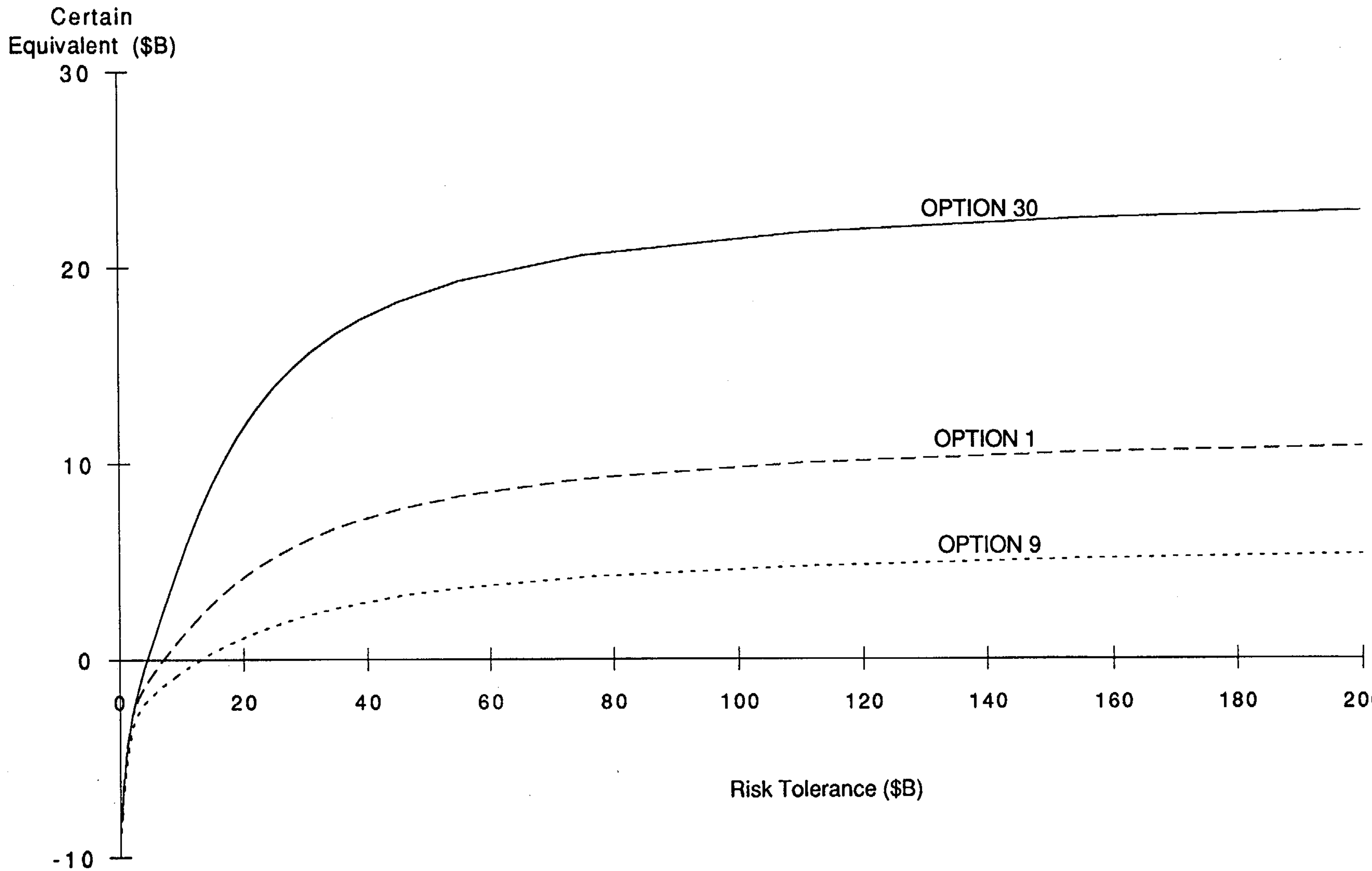

Figure 6-19. Sensitivity to Risk Attitude

TABLE 6-6

RANK ORDER FOR NEUTRAL, MODERATE, AND HIGH RISK AVERSION

Risk Neutral (no aversion to risk)		Low Risk Aversion (R=100 $B)		High Risk Aversion R=(20 $B)	
Option	Certain Equivalent = Exp. Net Benefit ($B)	Option	Certain Equivalent ($B)	Option	Certain Equivalent ($B)
30	24.4	30	21.5	30	11.8
23	23.4	23	20.5	23	11.2
24	23.0	24	20.1	24	10.7
13	22.7	13	19.8	13	10.5
6	22.3	6	19.4	6	10.4
7	22.0	7	19.2	7	10.2
2	20.8	2	18.1	2	9.5
19	20.4	19	17.7	19	9.1
25	19.9	25	17.0	4	8.6
4	19.7	4	16.9	21	8.5
21	19.6	21	16.8	25	8.3
28	19.2	28	16.4	28	8.1
22	17.8	22	15.0	22	7.1
29	17.0	29	14.3	32	7.1
32	16.8	32	14.2	29	6.7
27	16.4	20	13.8	20	6.6
20	16.3	27	13.6	15	6.4
8	16.0	8	13.4	8	6.3
31	15.9	31	13.2	31	6.0
15	15.5	15	13.0	33	6.0
33	15.2	33	12.7	27	6.0
5	14.5	5	12.1	5	5.5
12	13.8	12	11.4	16	5.2
3	13.7	16	11.3	12	5.1
16	13.7	11	11.2	11	5.0
11	13.5	1	9.8	1	4.2
1	12.1	14	9.2	14	3.8
14	11.4	10	9.0	18	3.7
10	11.2	18	8.9	10	3.5
18	11.0	17	8.8	17	3.5
17	11.0	34	7.8	34	2.9
34	9.8	26	5.9	26	1.8
26	7.7	3	4.6	3	1.1
9	6.2	9	4.6	9	1.1

R = Risk Tolerance

7.0 SUMMARY, CONCLUSIONS, AND INSIGHTS

7.1 Summary

The principal purpose of the ESF-AS was to comparatively evaluate and rank order 34 ESF-repository options. This was successfully accomplished by conducting a formal decision analysis that relied on inputs provided by expert panels, informed and aided, to the extent possible, by available data and relevant analyses. The comparative evaluation was a key component of the larger study as described in Section 1, Figure 1-1 of this report.

The comparative evaluation of ESF-repository options explicitly considered two distinct types of impacts of the ESF decision -- (1) the impact of the choice on the likelihood of alternative future scenarios and (2) the impact of the choice on the end consequences of the scenarios. The future scenarios, for which probabilities were estimated, included five scenarios leading to abandonment of the site and one scenario wherein the repository would be constructed, operated, and closed. The end consequences estimated for each scenario and each option included cost and schedule, preclosure health and safety impacts to repository workers and members of the public, environmental impacts on historical properties and the aesthetic quality of the area, and radionuclide releases following closure of the repository. In addition to providing best-judgment estimates for probabilities and end consequences, high and low estimates were generated to quantify uncertainties.

The comparative evaluation also accounted for the relative value of achieving favorable end consequences of various types. For example, tradeoff values between costs and postclosure releases were estimated. Value tradeoffs were used to convert the various types of end consequence estimates into a single measure of the net benefit of each option and each scenario, expressed in equivalent dollars. Although the nominal analysis assumed specific tradeoff values, ranges of values were estimated to account for different opinions as to what the tradeoffs should be. Sensitivity analysis showed, however, that the rank order of options was not very sensitive to the variations in tradeoff values.

7.2 Major Conclusions and Insights

The results of the analysis, described in previous sections of this volume, suggest conclusions and insights of four general types. As described below, these include

- Relative insensitivity of the rank order of options to variations in judgmental assessments,
- Importance of uncertainties about the ability to obtain a closed repository,
- Importance of near-term success in maintaining a viable repository program, and
- Features that enhance a favorable evaluation of ESF-repository.

7.2.1 Ranking Results

Significant uncertainties exist about the projected performance of the 34 options. However, a single overall ranking of the options was obtained, consistent with the majority opinions of the expert panels (Table 6-1). The nominal analysis, based on the consensus, best-judgment estimates provided by the majority of members of expert panels, identified 3 option pairs (6 and 23, 7 and 24, and 13 and 30) as being preferable to other options. A single option, Option 30, was identified as being most preferred.

The significance of the ranking results, in view of the uncertainties inherent in the analysis, is an important consideration for decision makers. The significance can be clarified, to a degree, by considering the differences in computed expected net benefits. For example, the difference between the expected net benefits computed for the options ranked first and second is roughly $1 billion ($24,411 million - $23,369 million = $1,042 million). This means that decision makers should prefer the first-ranked option over the second-ranked option by an amount equal to the preference for saving $1 billion in current dollars, assuming that the benefit of having a closed repository is $50 billion and that decision makers accept the assumptions underlying the analysis. If the benefit of a closed repository is more or less than $50 billion, the difference will be more or less than $1 billion (see Figure 6-3). In any case, a difference in expected net benefits on the order of a billion dollars is obviously significant. In other words, Option 30 would appear to be much preferable to the other options.

This conclusion must be tempered, however, by an awareness of the very large uncertainties in the evaluation. The cumulative probability distributions presented in Figure 6-9 demonstrate the considerable uncertainty that exists over the actual consequences of choosing an option. Thus, the second-ranked option, or in fact, any option, could turn out to produce better consequences than Option 30. Furthermore, the high and low estimates provided by expert panels to indicate each panel's confidence in its judgmental assessments indicate considerable uncertainty. Sensitivity analyses show that changes in option rankings can occur even if such uncertainties are completely correlated across options. In other words, if the inputs for all options were set at the most favorable or least favorable levels, the ranking of options would be somewhat different than that obtained in the nominal analysis.

In view of the very large uncertainties in the estimates provided by the expert panels and the many assumptions inherent in the evaluation, the precise expected net benefit estimates and detailed rankings resulting from the evaluation cannot be accepted with absolute certainty. Indeed, in several cases, all members of a panel could not reach consensus over what high, low, and best-judgment estimates should be used as input to the analysis. Nevertheless, sensitivity analyses indicated that the ranking of options was surprisingly robust. In particular, the same three option pairs are at or near the top of the ranking for many of the sensitivity studies and (with the exception of programmatic viability) regardless of which minority reports are assumed.

7.2.2 Importance of Uncertainties About the Ability to Obtain a Closed Repository

The rank ordering was determined almost entirely by the relative likelihood of obtaining a closed repository. As demonstrated by the sensitivity analyses in Section 6, the ranking of the options was relatively insensitive to the small differences estimated for the end consequences of the various scenarios. Similarly, the ranking was not very sensitive to the uncertainties of these end consequence estimates. Instead, the ranking was determined by the relative probabilities of important future events, such as programmatic viability and regulatory approval. In other words, the options were expected to differ very little in terms of their technical performance. Assuming that the repository would be developed at the Yucca Mountain site, all options were judged to provide acceptable performance; for example, any possible release of radionuclides from the emplacement areas to the water table were estimated to be almost certainly far below the EPA release limits.

The small differences in projected technical performance were overshadowed by the much larger differences estimated for factors considered to be important in achieving a closed, functioning repository. Thus, the real threat, if these results are to be believed, is not that an ESF-repository design might fail to perform well, but that the repository will fail to be developed at the Yucca Mountain site. The analysis suggests that an option should be selected based on its ability to promote necessary political and technical consensus. Although technical performance is obviously important in selecting an option, achieving high confidence within the DOE community in technical performance is far less important at this time than obtaining acceptance by other stakeholders in the process.

7.2.3 Importance of Programmatic Viability

Section 6 demonstrated that near-term success in maintaining a viable repository program was the most significant determinant of the rank ordering of options. The reason for this is that the majority consensus judgment from the Expert Panel on Programmatic Viability was that there is a significant risk that the Yucca Mountain effort will be abandoned before the initiation of characterization testing. Because the option selection was thought to significantly affect the likelihood of programmatic viability, these differences have a major impact on the relative ranking of options.

Of the various factors identified as significantly influencing programmatic viability, correlation analyses and comments by panel members suggest that the most important factor in the minds of the Expert Panel on Programmatic Viability was the degree to which the selected option addresses the concerns raised by the NRC and NWTRB (Table 6-4). To support the evaluations by the Panel, ESF-AS participants estimated the degree to which each option would likely be perceived as responsive to these concerns. The opinions and preferences of the NRC and NWTRB were not obtained directly as part of the study.

Given the significant risk of failing to maintain programmatic viability, as estimated by the majority of panel members, close interaction with agencies having regulatory authority, oversight committees, and other stakeholders would appear to be critical to the success of the repository program.

7.2.4 Features of ESF-Repository Options Important to Obtaining a Favorable Evaluation

A list of potentially favorable features of ESF-repository options is provided in Volume 1 (Table 6-4 in Section 6.3.3 of Volume 1). This section demonstrates that these features can be derived directly from the results of the comparative evaluation. The analysis involves recognizing that the highest-ranked options possess specific features that enhanced their favorable evaluations. Identification of these features provides a menu from which an improved option can be conceptualized and designed.

The specific features responsible for favorable evaluations can be deduced by answering three questions.

1. Which performance measures are most important in determining an option's overall ranking?

2. What critical factors influenced the estimates of the expert panels for the performance measures that are most important?

3. What features or collection of features led the expert panels to evaluate favorably options with respect to the critical factors and, therefore, to estimate favorable performance on the measures that are most important?

The sensitivity studies described in Section 6 provide the answer to the first question. The answer to the second question is provided by the influence diagrams and the various correlation studies described in the previous sections. The answer to the third question is provided by the detailed logic used by the expert panels during the scoring process -- that is, the logic used by the panel members to evaluate each option, relative to the base case, with respect to the double-bubbled factors in the influence diagrams.

Figure 7-1 summarizes the answers to the above questions in the form of an influence diagram. This influence diagram represents an aggregation of all of the influence diagrams developed for the study. For simplicity, all but the most significant factors have been removed. At the top level of the diagram, the probability of a closed repository is shown as the only factor significantly influencing expected net benefit. The second level of the diagram shows the four probabilities having the greatest influence on the probability of obtaining a closed repository -- programmatic viability, the outcome of early testing, the outcome of late testing, and regulatory approval.

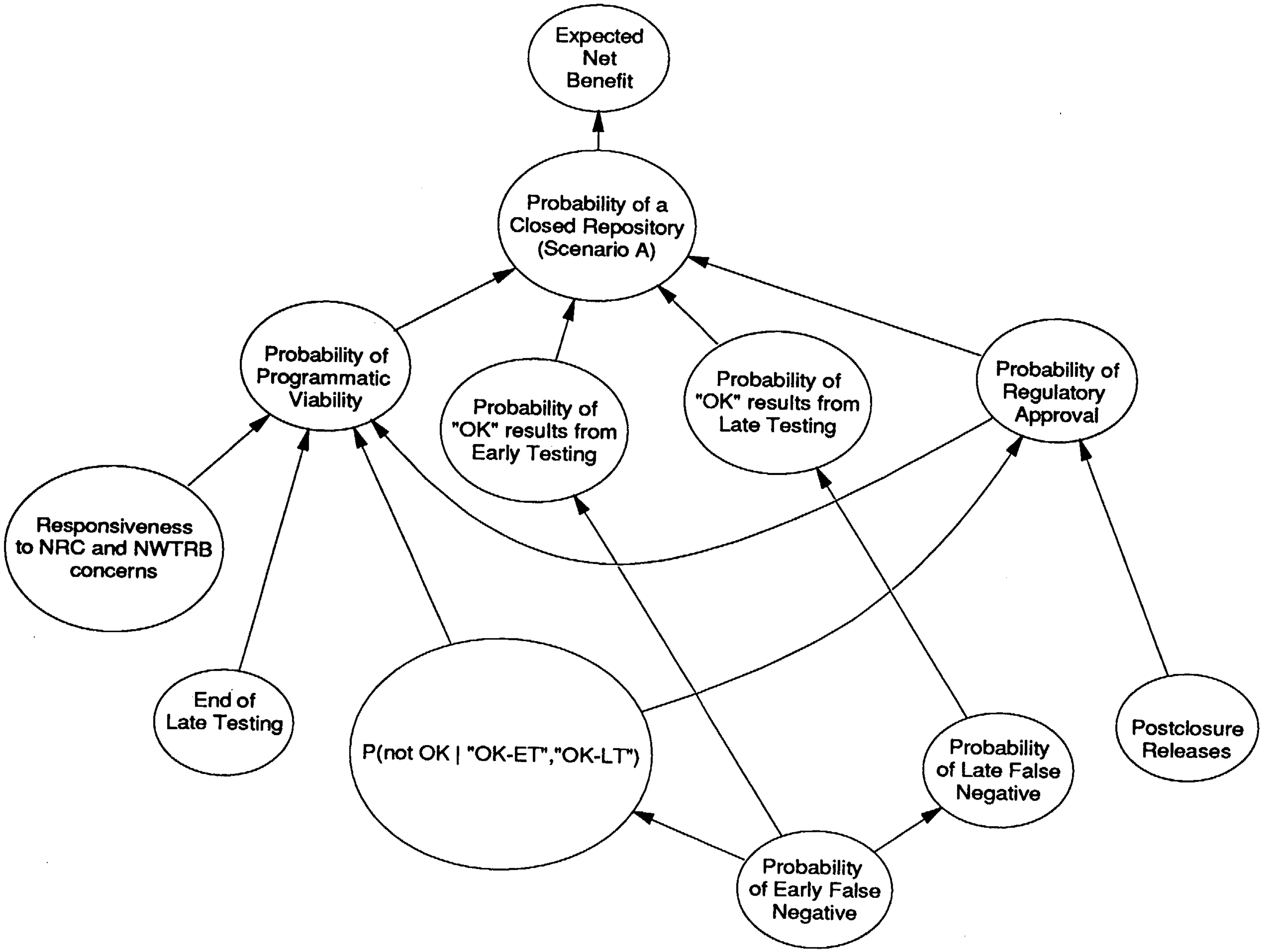

Figure 7-1. Influence Diagram Showing the Most Significant Factors in the ESF-AS

The most significant factors influencing the probability of programmatic viability are responsiveness to NRC and NWTRB concerns and the date on which late testing ends (the target date for submittal of the license application). The probabilities in Nature's Tree that have the greatest influence on the probability of "OK" results from testing are the probabilities of early and late false negatives. Postclosure releases and the residual probability that the site is NOT OK after testing, P(NOT OK/"OK-ET","OK-LT") , are the key factors influencing the probability of regulatory approval. Since the estimates for residual probability and probability of regulatory approval were also used by the panel that provided the probabilities of programmatic viability, arrows are drawn between these bubbles in the diagram.

Considering the principal factors in the influence diagram of Figure 7-1, the results of the comparative evaluation can now be summarized in terms of design and testing features that should be incorporated into an option. Specifically, Figure 7-1 and the logic used by expert panels in scoring suggest the following recommendations for an ESF option:

1. **During exploratory drifting in the TS unit, intercept the Ghost Dance Fault at more than one location.**

2. **Construct an east-west drift in the TS unit to expose any yet undiscovered north-south trending faults in the repository block.**

3. **Use a larger dedicated MTL to permit additional tests not included in the SCP and to allow sufficient spatial separation to avoid any test-to-test or construction-to-test interferences.**

The above three features improve the evaluation of an option because they were specifically recommended by NRC and NWTRB. These features were included in all options except Option 1. Inclusion of these features tended to improve the programmatic viability assessments relative to the base case.

Additional features recommended by the NRC and/or NWTRB were incorporated into a smaller subset of options. The following actions to incorporate such features tended to strengthen options and increase probabilities of programmatic viability and often tended to improve the evaluations with respect to other factors shown in Figure 7-1 as well.

4. **Use at least one ramp access for the ESF.**

Ramp accesses allow for examination of more rock than do shafts, and the incline of the ramp permits investigations of the structure. The three top-ranked option pairs all use at least one ramp, and four of them use two ramps for the primary accesses. Options with ramp accesses to the ESF have the advantage of providing site characterization data off the main block.

5. **Use mechanical mining methods, where appropriate.**

The NWTRB expressed a preference for mining methods that produce relatively smooth rock walls. Thus, options relying on mechanical mining techniques tended to be more highly rated with respect to responsiveness to NWTRB concerns. Such methods were also estimated by the Expert Panel on Characterization Testing to reduce the potential for test-to-construction interference. In some instances, mechanical mining may be preferable to minimize mechanical and/or chemical disturbances to the rock. The overall ranking clearly indicates that options using mechanical-excavation techniques (as opposed to drill-and-blast methods) rank higher. Although options using mechanical excavation methods ranked higher with respect to programmatic viability and the overall ranking, options using drill-and-blast methods ranked higher with respect to characterization testing.

6. **Expose large amounts of the rock, both on and off the main block.**

According to the majority view of the Expert Panel on Characterization Testing, options that provide exploration and testing of a large amount of the repository block and adjacent blocks during the characterization program reduce the likelihood of false-negative test outcomes by ensuring that ample opportunity will be available for identifying and refuting anomalous test results. Several highly rated options, including Option Pair 13 and 30 and Option 4, for example, offer the advantage of providing exploration and testing of large amounts of the repository block and the adjacent blocks during testing. Part of the motivation for the recommendation to use ramp accesses, discussed above, is the large exposure of rock produced with ramps.

7. **Provide adequate physical space for test flexibility.**

Options that provide for flexibility for the location of the MTL at either end of the block, as well as the ability to distribute tests along the north-south drift in the TS unit, reduce the likelihood of false-negative test outcomes by ensuring the ability to change and expand the testing program as needed to respond to possibly anomalous test results.

8. **Maximize distance between the waste emplacement areas and the water table.**

The "step-block" configurations of the waste emplacement areas of two option pairs (15 and 32 and 16 and 33) took advantage of preliminary indications of a shallower contact between the host rock unit Middle Topopah Spring Member (TSw2) and the overlying rock unit Upper Topopah Spring Member (TSw1) to increase the distance between the waste-emplacement horizon and the saturated zone. The nominally 50 percent greater distance between the waste-emplacement levels and the water table was responsible, in part, for the high rankings that these options received when panelists considered radionuclide releases. Placement of the waste farther above the water table increases the time required to transport radionuclides through the rock to the saturated zone.

9. **Avoid emplacement drifts crossing the Ghost Dance Fault.**

Another apparently advantageous feature of the stepped-block configurations used in the Option Pairs 15 and 32 and 16 and 33 is that no waste-emplacement drifts were designed to cross the Ghost Dance Fault. The importance of this feature depends on characteristics of the Fault discovered during site exploration and testing. This feature may be incorporated into the repository design, depending on the results of site characterization.

10. **Avoid constructed pathways for gravity flow from the TS unit to the CH unit.**

The highest ranked option (Option 30) provides no shaft, internal ramp, or other constructed pathway for gravity flow of water from the waste-emplacement level in the TS unit to the exploration level in the CH unit. This feature was very favorable for avoiding releases of radionuclides during postclosure. It is preferable that there are no mined connections between the emplacement areas and units closer to the saturated zone.

11. **Minimize the total number of accesses.**

The overall ranking of the options clearly indicates that options with fewer repository accesses rank higher. For example, all of the options in which the potential repository has both a single level and a total of four accesses ranked in the top five. The ranking of options based on postclosure releases shows a similar trend. For an operating repository, four accesses appears to be the minimum acceptable number of openings for a viable repository that requires two separate ventilation systems (one for mining and one for emplacement area).

12. **Support early site-suitability tests.**

The six most highly ranked options represent three pairs of ESF designs. One design of each pair features early access to the TS unit, and one design features early access to the CH unit. The three options designed to allow examination of the CH unit for purposes of site suitability ranked highest. The scoring results show that early tests for site suitability were clearly important to the DOE Management Panel, the Expert Panel on Programmatic Viability, and the Expert Panel on Regulatory Considerations. The scoring results from the Expert Panel on Programmatic Viability clearly indicate that these panel members believe such tests to be important to interested parties outside the DOE, such as the NWTRB and the NRC. Testing strategies and methodologies that show clear evidence of information being gathered that can be used to determine the "unsuitability" of the site will be perceived as technically credible and procedurally sound. Early tests for site suitability also affect the estimated degree of compliance with procedural requirements, which increases the probability that the site will be approved.

13. **Provide for extended duration tests.**

The probability of approval was enhanced by maintaining the ability to conduct extended duration tests. The flexibility to conduct extended duration tests affects the confidence in the technical program and the procedural administration of the ESF-repository. ESF designs can be enhanced with regard to extended duration tests by: (a) maximizing the size and location of the MTL, (b) optimizing the locations of the shop in relation to the test area, (c) reducing the potential for test interference from construction and from other test activities, (d) minimizing the amount of water used in construction, and (e) retaining the flexibility to expand shaft diameters by reaming.

14. **Allow for high-level waste tests.**

The Expert Panel on Regulatory Considerations assigned higher probabilities of approval to those options that allow for the high-level waste (HLW) tests. Although the DOE does not currently plan any HLW tests, options that accommodate the space required for the tests, use ramps for access, expose rocks likely to represent the geology in the repository block, and allow time in the testing schedule for HLW tests were considered more likely to receive regulatory approval. Those options that permit the appropriate tests were considered more likely to increase confidence in the implementation of a performance confirmation plan. For example, Option 7 was assigned a higher probability of approval (P_{APP}) than Option 24 because, in part, Option 24 was judged not as likely to accommodate the HLW tests as Option 7.

ACRONYMS FOR VOLUME 2

BLM	Bureau of Land Management
BRWM	Board of Radioactive Waste Management
BWR	boiling water reactor
CFM	cubic feet per minute
CFR	Code of Federal Regulations
CH	Calico Hills
D&E	development and evaluation
DEIS	Draft Environmental Impact Statement
DOE	U.S. Department of Energy
EBS	engineered barrier system
EPA	Environmental Protection Agency
ESF	Exploratory Studies Facility
ESF-AS	Exploratory Studies Facility Alternatives Study
FPCD	final procurement and construction design
ha	hectares of disturbed area
HEPA	high efficiency particulate air
HLW	high-level waste
HQ	headquarters
LAD	license application design
LOE	level of effort
MGDS	mined geologic disposal system
MRS	material retrieval system
MTHM	metric tons of heavy metal
MTL	main test level
MTU	metric tons uranium
MUA	multiattribute utility analysis
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
NWTRB	Nuclear Waste Technical Review Board
OCRWM	Office of Civilian Radioactive Waste Management
P_{VIAB}	probability of programmatic viability
P_{APP}	probability of approval
P_{CLO}	probability of repository closure

P_{RET}	probability of retrieval
P_{EFP}	probability of early false positive
P_{LFP}	probability of late false positive
P_{EFN}	probability of early false negative
P_{LFN}	probability of late false negative
P_{OK}	probability that the site is OK
PWR	pressurized water reactor
rem	roentgen equivalent man
RIB	Reference Information Base
RLCC	repository life-cycle costs
SBT	surface-based testing
SCP	Site Characterization Plan
SNL	Sandia National Laboratories
SRI	Stanford Research Institute
TBM	tunnel boring machine
TS	Topopah Spring
TSLCC	total system life-cycle costs
TSw1	Upper Topopah Spring Member
TSw2	Middle Topopah Spring Member
UG	underground
YMP	Yucca Mountain Site Characterization Project
YMPO	Yucca Mountain Site Characterization Project Office

REFERENCES FOR VOLUME 2

Bonano, E.J., S.C. Hora, R.L. Keeney, and D. von Winterfeldt, 1990. "Elicitation and Use of Expert Judgment in Performance Assessment for High-Level Radioactive Waste Repositories," (NUREG/CR-5411, SAND89-1821), prepared for U.S. Nuclear Regulatory Commission [by] Sandia National Laboratories, NRC, Washington D.C., May. (NNA.910617.0007)

Bunn, D.W., 1984. *Applied Decision Analysis*, McGraw-Hill, New York. (NNA.910816.0053)

Chankong, V., and Y.Y. Haimes, 1983. *Multiobjective Decision Making: Theory and Methodology*, North-Holland/Elsevier, New York, pp. 186-188. (NNA.910809.0014)

DOE (U.S. Department of Energy), 1986. A Multiattribute Utility Analysis of Sites Nominated for Characterization for the First Radioactive-Waste Repository -- A Decision-Aiding Methodology (DOE/RW-0074), Office of Civilian Radioactive Waste Management, Washington D.C. (NNA.870818.0022)

DOE (U.S. Department of Energy), 1988. Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada (DOE/RW-0160), Office of Civilian Radioactive Waste Management, Washington D.C. (HQS.880517.0937-.0943)

EPA (U.S. Environmental Protection Agency), 1987. "Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-level and Transuranic Radioactive Wastes," (Code of Federal Regulations, Protection of Environment, Title 40, Part 191), Washington D.C. (NNA.910306.0125)

Graham, J.D., and J.W. Vaupel, 1981. "Value of a Life: What Difference Does It Make?", Risk Analysis 1(1), 89-95. (NNA.910617.0015)

Hays, W.L., and R.L. Winkler, 1971. *Statistics: Probability, Inference, and Decision*, Holt, Rinehart and Winston, New York, pp. 839-845. (NNA.910821.0042)

Hobbs, B.F., 1982. Analytical Multi-objective Decision Methods for Power Plant Siting: A Review of Theory and Applications (NUREG/CR-1687, BNL-NUREG-51204), prepared for the U.S. Nuclear Regulatory Commission [by] Brookhaven National Laboratory, Uptown, NY. (NNA.910617.0001)

Howard, R.A., 1990. "From Influence to Relevance to Knowledge," pp. 3-23 in R.M. Oliver and J.Q. Smith (eds.), *Influence Diagrams, Belief Nets, and Decision Analysis* [Proceedings of the Conference on Influence Diagrams for Decision Analysis, Inference, and Prediction, held May 9-11, 1988, University of California, Berkeley], John Wiley and Sons, Chichester and New York. (NNA.910816.0056)

Howard, R.A., 1968. "The Foundations of Decision Analysis," *IEEE Transactions on Systems Science and Cybernetics* **SSC-4**(3), 211-19. (NNA.910617.0016)

Keeney, R.L., 1976. "A Group Preference Axiomatization with Cardinal Utility," Management Science **23**(2), 140-45. (NNA.910701.0094)

Keeney, R.L., 1977. "The Art of Assessing Multiattribute Utility Functions," Organizational Behavior and Human Performance **19**(2), 267-310. (NNA.910701.0095)

Keeney, R.L., 1981. "Analysis of Preference Dependencies Among Objectives," Operations Research **29**, 1105-20. (NNA.910617.0020)

Keeney, R.L., and H. Raiffa, 1976. *Decisions with Multiple Objectives*, John Wiley and Sons, New York. (NNA.910819.007)

Luce, R.D., and H. Raiffa, 1957. *Games and Decisions*, John Wiley and Sons, New York, pp. 25-31. (NNA.910809.0011)

Merkhofer, M.W., 1987a. "Quantifying Judgmental Uncertainty: Methodology, Experiences, and Insights," *IEEE Transactions on Systems, Man, and Cybernetics* **SMC-17**(5), 741-52, September/October. (NNA.910617.0013)

Merkhofer, M.W., 1987b. *Decision Science and Social Risk Management: A Comparative Evaluation of Cost-Benefit Analysis, Decision Analysis, and other Formal Decision-Aiding Approaches*, D. Reidel Publishing Co., Dordrecht, The Netherlands. (NNA.910812.0003)

Merkhofer, M.W., 1990. "Using Influence Diagrams in Multiattribute Utility Analysis -- Improving Effectiveness Through Improving Communication," pp. 297-317 in R.M. Oliver and J.Q. Smith (eds.), *Influence Diagrams, Belief Nets, and Decision Analysis* [Proceedings of the Conference on Influence Diagrams for Decision Analysis, Inference, and Prediction, held May 9-11, 1988, University of California, Berkeley], John Wiley and Sons, Chichester and New York. (NNA.910816.0054)

Merkhofer, M.W., and R.L. Keeney, 1987. "A Multiattribute Utility Analysis of Alternative Sites for the Disposal of Nuclear Waste," Risk Analysis 7(2), 173-94, June. (NNA.910617.0017)

NRC (Nuclear Regulatory Commission), 1983. "Safety Goals for Nuclear Power Plants," NUREG-0880, Office of Policy Evaluation, February. (NNA.910816.0058)

NRC (Nuclear Regulatory Commission) 1989. "NRC Staff Site Characterization Analysis of the Department of Energy's Site Characterization Plan, Yucca Mountain Site, Nevada." Office of Nuclear Materials on Safeguards. NUREG-1347, August. (NNA.891020.0161)

NWTRB, (Nuclear Waste Technology Review Board), 1989. Transcript of DOE Briefing by NWTRB, Structural Geology and Geoengineering Panel, April 11-12. (NNA.910819.0008)

NWTRB, (Nuclear Waste Technology Review Board), 1990. First Report to the U.S. Congress and the Secretary of Energy from the Nuclear Waste Technical Review Board. (NNA.900413.0058)

Raiffa, H., 1968. *Decision Analysis: Introductory Lectures on Choices under Uncertainty*, Addison-Wesley, Reading, MA. (NNA.910816.0055)

Rowe, M.D., B.F. Hobbs, B.L. Pierce, and P.M. Meier, 1981. An Assessment of Nuclear Power Plant Siting Methods" (NUREG/CR-1689, BNL-NUREG-51206), prepared for the U.S. Nuclear Regulatory Commission [by] Brookhaven National Laboratory, Uptown, NY, July. (NNA.910701.0092)

Shachter, R., 1986. "Evaluating Influence Diagrams," Operations Research 34(6), 871-82. (NNA.910617.0003)

Spetzler, C.S., and C.-A.S. Stael von Holstein, 1975. "Probability Encoding in Decision Analysis," Management Science **22**, 340-58. (NNA.910701.0096)

Stael von Holstein, C.-A.S., and J.E. Matheson, 1979. A Manual for Encoding Probability Distributions (SRI Project 7078), SRI International, Menlo Park, CA. (NNA.910701. 0090)

Stokey, E., and R. Zeckhauser, 1978. *A Primer for Policy Analysis*, Norton, New York. (NNA.910812.0010)

Thompson, M.S., 1982. Decision Analysis for Program Evaluation, Ballinger, Cambridge, MA. (NNA.910703.0004)

Tversky, A., and D. Kahneman, 1974. "Judgment Under Uncertainty: Heuristics and Biases," Science **165**, 1232-38. (NNA.910701.0091)

Tversky, A., and D. Kahneman, 1981. "The Framing of Decisions and the Psychology of Choice," Science **211**, 453-58, January 30. (NNA.910617.0018)

APPENDIX A

PARTICIPANTS IN THE ESF-AS COMPARATIVE EVALUATION

APPENDIX A

PARTICIPANTS IN THE ESF-AS COMPARATIVE EVALUATION

This appendix identifies the participants and their roles in the development and implementation of the methodology that was used for the comparative evaluation of 34 ESF-repository Options in the ESF Alternatives Study. About 80 people, consisting of DOE managers, SNL managers and staff, technical specialists from support contractors, and consultants participated in the comparative evaluation. The process began in January of 1990 and was completed in May 1991.

A general flow diagram showing the process for implementing the methodology is presented in Figure A-1. The participants are listed in Tables A-1 through A-5, together with their organizational affiliations, qualifications, and the roles they played in the development and application of the methodology.

The methodology lead group was responsible for developing the logical basis for the application of the methodology, for guiding all participants through the required steps of the methodology, and for eliciting from the technical staff and management the technical and value judgments required to implement the methodology. In addition, the group was responsible for compiling and editing Volume II of the ESF-AS final report. The group was under the general oversight of the SNL Management Lead Group identified in Table A-1.

The groups of technical specialists are organized by discipline in Tables A-2 and A-5. They were responsible for developing, with guidance from the methodology lead group, the influence diagrams, and associated performance measures for the various consequence objectives. They were also responsible for scoring the options against the performance measures. Several members of technical panels also provided support for design, characterization testing, and cost for other panels.

Several DOE and SNL managers, listed in Table A-2, participated in those parts of the methodology that require value or policy judgments. These included, in particular, the specification of consequence objectives, the verification of independence assumptions, and the specification of utility curves and weighting factors. In addition, the managers reviewed the progress of the implementation of the methodology at various times throughout the process.

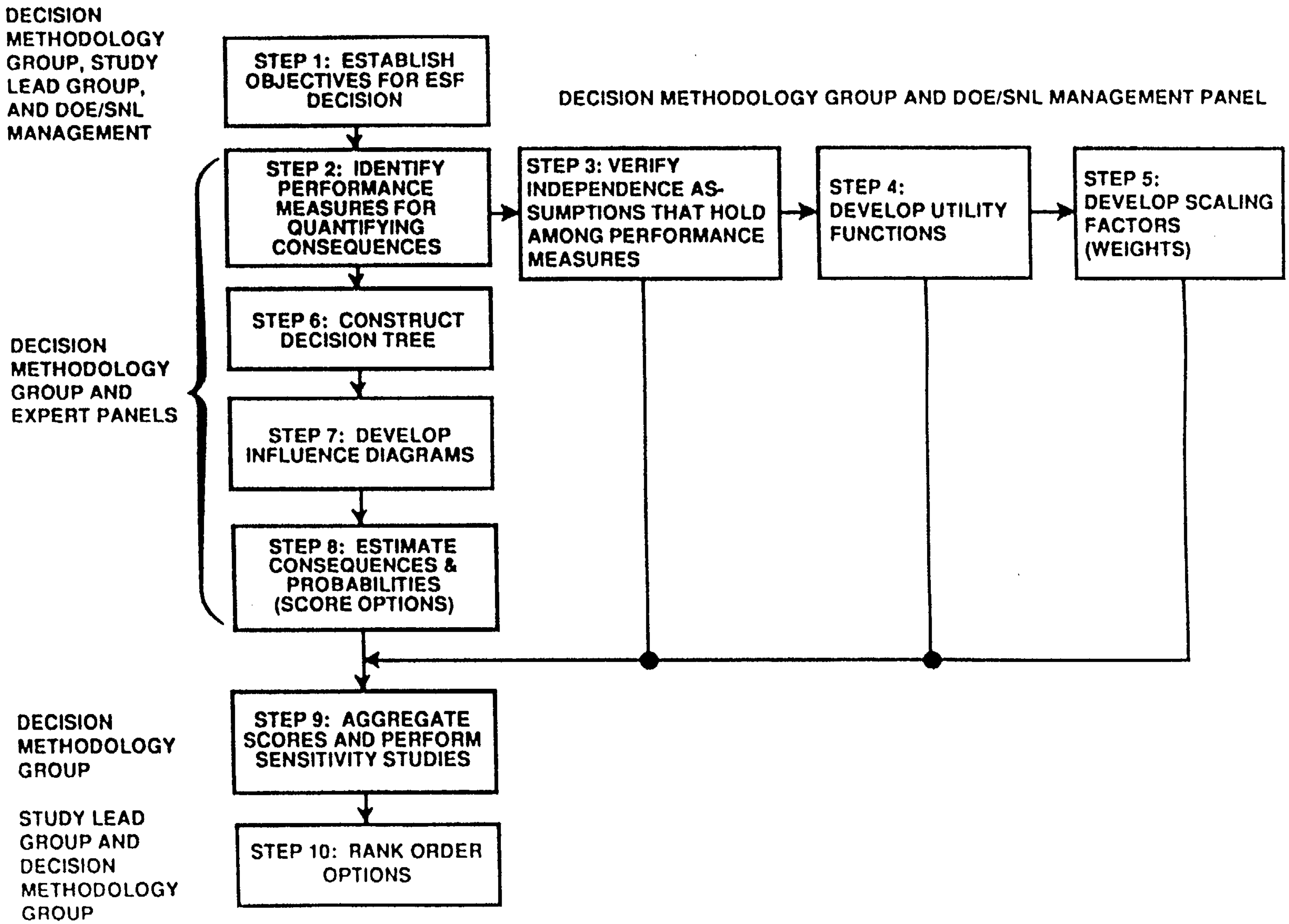

Figure A-1. General Flow of Activities and Division of Responsibilities for Implementing the Decision Aiding Methology.

TABLE A-1

PARTICIPANTS IN THE DEVELOPMENT AND IMPLEMENTATION OF THE METHODOLOGY

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Decision Analysis	Years of Professional Experience: Other	Role[a]
Sandia Management Lead Group							
Aldred Stevens	Sandia National Laboratories	Ph.D. Applied Mechanics Michigan State University (1968)	ESF-Repository Design Rock Mechanics High Rate Deformation	7		15	Lead; 1,2,6,7,8,10
Stephen Bauer	Sandia National Laboratories	Ph.D. Geology Texas A&M University (1983)	Rock Mechanics Numerical Modeling Tectonophysics	8		1	1,2,6,7,8,10
Larry Costin	Sandia National Laboratories	Ph.D. Engineering Mechanics Brown University (1978)	Micromechanics In Situ Testing Constitutive Models	5		13	1,2,6,10
Al Dennis	Sandia National Laboratories	M.S. Civil Engineering Structural Mechanics University of NM (1965)	Program Management Engineering Design Numerical Modeling	11		22	1,2,6,10
Decision Methodology Lead Group							
Lee Merkhofer	Applied Decision Analysis, Inc.	Ph.D. Engineering-Economic Systems Stanford University (1975)	Decision Analysis Risk Assessment Environmental Analysis		19	3	Lead; all steps
Paul Gnirk	RE/SPEC Inc.	Ph.D. Rock Mechanics University of Minnesota (1966)	Rock Mechanics Repository Engineering DOE Siting Guidelines	20		10	Lead; all steps
Phillip Beccue	Applied Decision Analysis, Inc.	M.S. Engineering Economic Systems Stanford University (1990)	Decision Analysis Simulation Modeling		2	4	2,3,4,5,6,7,8,9,10

[a]The numbers in this column correspond to the steps in the methodology (Figure A-1).

TABLE A-1

PARTICIPANTS IN THE DEVELOPMENT AND IMPLEMENTATION OF THE METHODOLOGY
(Concluded)

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Decision Analysis	Years of Professional Experience: Other	Role[a]
William Boyle	RE/SPEC Inc.	Ph.D. Geological Engineering University of California Berkeley (1987)	Rock Mechanics Geology	6		5	7,8,9,10
David Parrish	RE/SPEC Inc.	Ph.D. Geology Rice University (1972)	Geology Numerical Modeling Tectonophysics	11		9	3,4,5,7,8,9,10
Jessica Rothberg	Applied Decision Analysis, Inc.	M.S. Data Analysis and Statistical Computing Stanford University (1987)	Data Analysis Computer Modeling		1	4	9

[a]The numbers in this column correspond to the steps in the methodology (Figure A-1).

TABLE A-2

DEPARTMENT OF ENERGY AND SANDIA NATIONAL LABORATORIES MANAGEMENT AND THEIR ROLES IN THE DEVELOPMENT AND IMPLEMENTATION OF THE METHODOLOGY

Name	Affiliation[a]	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other	Role[b]
Department of Energy and Sandia National Laboratories Management Panel						
Lake Barrett	Department of Energy	No Information Submitted				
Stephan Brocuom	Department of Energy	Ph.D. Structural Geology Columbia University (1971)	Siting and Licensing Plan Program Management Site Characterization			1
Maxwell Blanchard	Department of Energy/Yucca Mountain Project	M.S. Geology San Jose State University (1968)	Siting Licensing Geology Structural Analysis	11	25	1
Thomas Blejwas	Sandia National Laboratories	Ph.D. Civil Engineering University of Colorado (1978)	Radioactive Waste Storage Rock Mechanics Structural Analysis	6	16	1,3,4,5
Thomas Issacs	DOE/OCRWM	M.S. Engineering and Applied Physics Harvard University (1971)	Nuclear Engineering Nuclear Waste Management Science and Public Politics	7	15	1
Carl Gertz	Department of Energy/Yucca Mountain Project	M.S. Civil Engineering and Systems Management University of Southern CA (1971)	Waste Management Policy Environmental Management Program Management	15	15	1,3,4,5
Tom Hunter	Sandia National Laboratories	Ph.D. Nuclear Engineering University of Wisconsin (1978)	Program Management Nuclear Waste Management Nuclear Engineering	12	9	1,3,4,5
Leo Little	DOE[c]	B.S. Electrical Engineering Rose Hulman Institute of Technology (1952)	Project Management Nuclear Engineering Systems Analysis	7	32	1

[a]Abbreviations - DOE: Department of Energy, YMP: Yucca Mountain Project, OCRWM: Office of Civilian Radioactive Waste Management.
[b]The numbers in this column correspond to the steps in the methodology (Figure A-1).
[c]Current affiliation: Department of Energy, Richland Operations

TABLE A-2

DEPARTMENT OF ENERGY AND SANDIA NATIONAL LABORATORIES MANAGEMENT AND THEIR ROLES IN THE DEVELOPMENT AND IMPLEMENTATION OF THE METHODOLOGY
(Concluded)

Name	Affiliation[a]	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other	Role[b]
Richard Lynch	Sandia National Laboratories	Ph.D. Chemical Engineering University of Illinois (1966)	Planning Program Management Siting and Licensing	15	10	1
Edgar Petrie	Department of Energy/Yucca Mountain Project	B.S. Physics Brown University (1951)	Systems Engineering Project Management Design Engineering	7	33	1
Ralph Stein	Department of Energy[b]	B.S. Chemical Engineering University of Pittsburgh (1954)	Siting and Licensing Waste Management Policy Environmental Management	12	23	1,4,5
Wendell Weart	Sandia National Laboratories	Ph.D. Geophysics University of Wisconsin (1961)	Underground Explosions Underground Containment Nuclear Waste Management	16	19	1

[a]The numbers in this column correspond to the steps in the methodology (Figure A-1).
[b]Current affiliation: Science Applications International Corp.

TABLE A-3

POSTCLOSURE TECHNICAL SPECIALISTS AND THEIR ROLES IN THE DEVELOPMENT AND APPLICATION OF THE METHODOLOGY

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other	Role[a]
			Expert Panel on Postclosure Health			
Felton Bingham	Sandia National Laboratories	Ph.D. Nuclear Physics Indiana University (1962)	Performance Assessment Mill-Tailings Disposal Environmental Assessment	8	14	7,8
Evaristo Bonano	Sandia National Laboratories	Ph.D. Chemical Engineering Clarkson University (1980)	Transport Phenomena Waste Management Performance Assessment	8	4	7
Paul Davis	Sandia National Laboratories	Ph.D. Hydrology New Mexico Institute of Technology (1978)	Geohydrology Hydrology Risk Assessment	11	2	7
Joseph Fernandez	Sandia National Laboratories	M.S. Geological Engineering University of Arizona (1978)	Sealing Boreholes Sealing Tunnels Performance Assessment	12	-	7
Michael Hardy	J.F.T. Agapito Associates	Ph.D. Geoengineering University of Minnesota (1973)	Rock Mechanics Thermomechanical Analysis Mine Design	12	8	8
Thomas Hinkebein	Sandia National Laboratories	Ph.D. Chemical Engineering University of Washington (1976)	Sealing Performance Assessment Hydrology	6	16	7,8
Dwight Hoxie	U.S. Geological Survey	Ph.D. Astrophysics University of Arizona (1969)	Hydrological Inv. Numerical Modeling Fluid Mechanics	6	-	8
Barney Lewis	U.S. Geological Survey	M.S. Geology Montana State University (1974)	Groundwater Hydrology Groundwater Chemistry	4	13	7

[a]The numbers in this column correspond to the steps in the methodology (Figure A-1).

TABLE A-3

POSTCLOSURE TECHNICAL SPECIALISTS AND THEIR ROLES IN THE DEVELOPMENT AND APPLICATION OF THE METHODOLOGY
(Concluded)

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other	Role[a]
Scott Sinnock	Sandia National Laboratories	Ph.D. Geology Geomorphology Purdue University (1978)	Geology Performance Assessment Numerical Modeling	12	4	7,8
Michael Voegele	Science Applications International Corp.	Ph.D.Geological Engineering University of Minnesota (1978)	Geotechnical Engineering Siting and Licensing Environmental Assessment	12	8	7,8
Michael Wilson	Sandia National Laboratories	Ph.D. Physics University of California Berkeley (1981)	Numerical Modeling Performance Assessment	6	2	7,8
Brian Ehgartner	Sandia National Laboratories	M.S. Civil Engineering University of West Virginia (1984)	Geomechanics Structural Analysis Yucca Mountain Site	5	2	7

[a]The numbers in this column correspond to the steps in the methodology (Figure A-1).

TABLE A-4

PRECLOSURE TECHNICAL SPECIALISTS AND THEIR ROLES IN THE DEVELOPMENT AND IMPLEMENTATION OF THE METHODOLOGY

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other	Role[a]
Expert Panel on Preclosure Radiological Health						
Paul Harris	HLB Advanced Systems	M.S. Nuclear Engineering University of California, Santa Barbara (1984)	Performance Assessment Safety Assessment Nuclear Engineering	8	18	7
Leslie Jardine	Lawrence Livermore National Laboratories	Ph.D. Nuclear Engineering and Chemistry, University of California (1971)	Radiological Engineering Repository Design Waste Package	15	5	7,8
Chin Ma	Bechtel National, Inc.[b]	Ph.D. Nuclear Physics Engineering, University of California, Berkeley (1969)	Radiological Assessment and Risk Analysis Repository Design	4	22	7,8
Daryl Miller	Bechtel National, Inc.	M.S. Nuclear Science and Engineering, Catholic University, Washington, DC (1978)	Nuclear Engineering Radiological Safety Repository Design	6	11	7,8
David Michlewicz	Roy F. Weston, Inc.[c]	M.S. Nuclear Engineering Columbia University (1974)	Health Physics Licensing Risk Analysis	14	17	7,8
Expert Panel on Preclosure Nonradiological Safety						
Reinhold Leske	Reynolds Electrical & Engineering Co. Inc.	B.S. Mineral Engineering University of Wisconsin (1957)	Mine Safety Mine Design Mine Safety Standards	-	25	7,8
Jacob Paz	Reynolds Electrical & Engineering Co. Inc.	Ph.D. Environmental Health Polytechnic University of New York (1984)	Industrial Hygiene Respiratory Equipment OSHA Compliance	2	7	7,8

[a]The numbers in this column correspond to the steps in the methodology (Figure A-1).
[b]Current affiliation: M. H. Chew & Associates Inc.
[c]Current affiliation: Department of Energy.

TABLE A-4

PRECLOSURE TECHNICAL SPECIALISTS AND THEIR ROLES IN THE DEVELOPMENT AND IMPLEMENTATION OF THE METHODOLOGY
(Continued)

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other	Role[a]
Robert Prichett	Reynolds Electrical & Engineering Co. Inc.	M.S. Mineral Engineering South Dakota School of Mines and Technology (1967)	Excavation Surface Construction Underground Construction	3	25	7,8
Archie Richardson	J.F.T. Agapito Associates	Ph.D. Mineral Engineering Colorado School of Mines (1986)	Rock Mechanics Mining Engineering Repository Engineering	8	12	7,8
Bruce Schepens	Reynolds Electrical & Engineering Co. Inc.	B.S. Mineral Engineering Virginia Polytechnic Institute and State University (1978)	Underground Construction Shaft Sinking Tunnel Excavation	2	11	7
Technical Experts on Environment						
Ted Doerr	EG&G Energy Systems	Ph.D. Wildlife Management and Range Management, Texas A&M University (1988)	Endangered Species Reclamation Applied Ecology	-	13	7
Gregory Fasano	Science Applications International Corp.	B.S. Geology San Diego State University (1982)	Environmental Management Environmental Regulations Geology	7	2	7,8
Asha Kalia	Raytheon Services Nevada	Ph.D. Archaeology University of Lucknow India (1974)	Archaeology QA Procedures QA Compliance	5	12	7
Ed McCann	Science Applications International Corp.	B.S. Forestry University of Michigan (1970)	Environmental Regulatory Compliance	8	13	7,8

[a]The numbers in this column correspond to the steps in the methodology (Figure A-1).

TABLE A-4

PRECLOSURE TECHNICAL SPECIALISTS AND THEIR ROLES IN THE DEVELOPMENT AND IMPLEMENTATION OF THE METHODOLOGY
(Continued)

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other	Role[a]
Lonnie Pippin	Desert Research Institute	Ph.D. Anthropology Washington State University (1979)	Archaeology Paleontological Research Cultural Resource	10	25	7,8
Thomas Pysto	Science Applications International Corp.	B.S. Wildlife Management Colorado State University (1975)	Environmental Legislation Applied Geology Environmental Compliance	4	12	7
David Rhode	Desert Research Institute	Ph.D. Archaeology University of Washington (1987)	Archaeology Paleoenvironment, Cultural Resource Management	-	15	7,8
Allan Smith	Raytheon Services Nevada	B.S. Biophysics Yale University (1957)	Health Physics Environmental Regulation Environmental Compliance	-	34	7
Expert Panel on Socioeconomics						
John Carlson	Science Applications International Corp.	M.A. Economics/Statistics University of Missouri (1975)	Economics Socioeconomic Impact Planning Methods	4	16	7
Carl Ellis	Science Applications International Corp.	M.A. Sociology University of Wyoming (1974)	Socioeconomic Analysis Intergovernmental Analysis Regulation Compliance	2	16	7
Robert Kimble	Science Applications International Corp.	M.A. Anthropology University of Wyoming (1976)	Socioeconomic Impact Research Design Environmental Impact	5	15	7

[a]The numbers in this column correspond to the steps in the methodology (Figure A-1).

TABLE A-4

PRECLOSURE TECHNICAL SPECIALISTS AND THEIR ROLES IN THE DEVELOPMENT AND IMPLEMENTATION OF THE METHODOLOGY
(Continued)

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other	Role[a]
Expert Panel on Cost and Schedule						
Frank Bugg	Roy F. Weston, Inc.	B.S. Engineering of Mines University of West Virginia (1980)	Life Cycle Cost Mining Engineering Geotechnical Engineering	3	9	8
Matthew Fowler	Parsons, Brinckerhoff, Quade & Douglas	M.S. Mining Engineering University of California Berkeley (1984)	Cost Analysis Repository Design Underground Construction	6	10	7,8
Bruce Gardella	Reynolds Electrical & Engineering Co. Inc.	B.S. Civil Engineering University of Nevada Reno (1968)	Mining Engineering Schedule Analysis Construction Engineering	3	25	8
Daniel Koss	Reynolds Electrical & Engineering Co. Inc.	B.S. Mining Engineering MI College of Mining & Technology (MI Tech University) (1960)	Mining Engineering Underground Construction	6	31	8
Gerry Woodard	Raytheon Services Nevada	Business Certificate La Salle University (1968)	ESF Design ESF Cost Analysis Construction Cost	6	22	7,8
Gregory Fasano	Science Applications International Corp.	B.S. Geology San Diego State University (1982)	Environmental Management Environmental Regulations	7	2	7,8
Tony Ivan Smith	Consultant	M.S.C. Mechanical Engineering/ Geology University of California (1991)	ESF Cost Analysis Tunneling Technology ESF Design	1	22	8
Jim Scott	Raytheon Services Nevada	B.S. Civil Engineering Tri-State University (1965)	Mine Design Mine Feasibility Cost Estimating	6	20	7,8

[a]The numbers in this column correspond to the steps in the methodology (Figure A-1).

TABLE A-4

PRECLOSURE TECHNICAL SPECIALISTS AND THEIR ROLES IN THE DEVELOPMENT AND IMPLEMENTATION OF THE METHODOLOGY
(Continued)

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other	Role[a]
Earl Gruer	Sandia National Laboratories	B.S. Mechanical Engineering University of New Mexico (1964)	HVAC Design Life Cycle Cost Mechanical Systems Design	9	23	7,8
Dennis Thomas	Raytheon Services Nevada		No Information Submitted			
Expert Panel on Regulatory Considerations						
Carl Brechtel	J.F.T. Agapito Associates	M.S. Mining Engineering University of Utah (1978)	Mine Design Mine Ventilation Geotechnical Engineering	8	16	7,8
Monica Dussman	Science Applications International Corp.		No Information Submitted			7
William McClain	Oak Ridge National Laboratory	Ph.D. Mining Engineering University of Newcastle-upon-Tyne (1963)	Program Management Waste Management Geotechnology	27	-	8
David Michlewicz	Roy F. Weston, Inc.[b]	M.S. Nuclear Engineering Columbia University (1974)	Health Physics Licensing Risk Analysis	14	17	7,8
Michael Glora	Science Applications International Corp.	B.A. Zoology Colorado College (1959)	Regulatory Compliance Licensing Health Physics	12	30	7

[a]The numbers in this column correspond to the steps in the methodology (Figure A-1).
[b]Current affiliation: Department of Energy.

TABLE A-4

PRECLOSURE TECHNICAL SPECIALISTS AND THEIR ROLES IN THE DEVELOPMENT AND IMPLEMENTATION OF THE METHODOLOGY
(Continued)

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other	Role[a]
Mark McKeown	U.S. Bureau of Reclamation	B.S. Engineering Geol. California State University Los Angeles (1967)	Geotechnical Explor., Design, Construction Engineering Geol.	5	20	7
Paul Thompson	Atomic Energy of Canada, Limited	B.A. Science Geol. Eng. University of Toronto (1975)	Geotechnical Engineering In Situ Testing Geotechnical Instrumentation	8	8	8
Ned Elkins	Los Alamos National Laboratory	Ph.D. Civil Engineering/ Biochemistry New Mexico State University (1982)	Hydrological Investigations Applied Ecology ESF Design	2	8	7,8
Michael Hardy	J.F.T. Agapito Associates	Ph.D. Geoengineering University of Minnesota (1973)	Rock Mechanics Thermomechanical Analysis Mine Design	12	8	7,8
Thomas Hinkebein	Sandia National Laboratories	Ph.D. Chemical Engineering University of Washington (1976)	Sealing Performance Assessment Hydrology	6	16	7,8
Michael Voegele	Science Applications International Corp.	Ph.D. Geological Engineering University of Minnesota (1978)	Geotechnical Engineering Siting and Licensing Environmental Assessment	12	8	7,8
		Expert Panel on Programmatic Viability				
Stephan Brocuom	Department of Energy	Ph.D. Structural Geology Columbia University (1971)	Siting and Licensing Plan Program Management Site Characterization			1

[a]The numbers in this column correspond to the steps in the methodology (Figure A-1).

TABLE A-4

PRECLOSURE TECHNICAL SPECIALISTS AND THEIR ROLES IN THE DEVELOPMENT AND IMPLEMENTATION OF THE METHODOLOGY
(Continued)

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other	Role[a]
Michael Parsons	Science Applications International Corp.	M.S. Geology University of North Dakota (1980)	Site Characterization Nuclear Regulatory Compliance Petroleum Exploration	6	5	7,8
Henry Bermanis	Roy F. Weston, Inc.	B.S. Physics and Math University of Cincinnati (1962)	Nuclear Engineering Licensing Regulatory Compliance	8	30	8
Roger Hill	Sandia National Laboratories	B.S.E. Electrical Engineering Kansas State University (1976)	Project Engineering Electrical Power Systems Project Management	5	10	7
Expert Panel on Characterization Testing						
Stephen Bauer	Sandia National Laboratories	Ph.D. Geology Texas A&M University (1983)	Rock Mechanics Numerical Modeling Tectonophysics	8	1	7,8
Robert Craig	U.S. Geological Survey	M.A. Physical Science California State University Chico (1976)	Hydrological Inv. Hydrogeology Geosciences	9	4	7,8
Richard Grenia	Research Services Nevada/Parsons Brinckerhoff	B.S. Mining/Geology University of Missouri Rolla (1958)	Engineering Design Mine Design Repository Engineering	7	32	7,8
Frank Hansen	Sandia National Laboratories	Ph.D. Geology Texas A&M University (1982)	Geomechanics Experimental Rock Mechanics	12	5	7,8
Hemendra Kalia	Los Alamos National Laboratory	Ph.D. Mining Engineering University of Missouri Rolla (1970)	Geotechnical Prog. Mine Design Rapid Excavation	8	15	7

[a]The numbers in this column correspond to the steps in the methodology (Figure A-1).

TABLE A-4

PRECLOSURE TECHNICAL SPECIALISTS AND THEIR ROLES IN THE DEVELOPMENT AND IMPLEMENTATION OF THE METHODOLOGY
(Concluded)

Name	Affiliation[a]	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other	Role[b]
Maxwell Blanchard	Department of Energy/Yucca Mountain Project	M.S. Geology San Jose State University (1968)	Siting and Licensing Geology DOE Siting Guidelines	11	25	7,8
Thomas Blejwas	Sandia National Laboratories	Ph.D. Civil Engineering University of Colorado (1978)	Radioactive Waste Storage Rock Mechanics Structural Analysis	6	16	7,8
Thomas Isaacs	DOE/OCRWM	M.S. Engineering and Applied Physics Harvard University (1971)	Nuclear Engineering Nuclear Waste Management Science & Public Politics	7	15	8
Carl Gertz	Department of Energy/Yucca Mountain Project	M.S. Civil Engineering and Systems Management University of Southern CA (1971)	Waste Management Policy Environmental Management Program Management	15	15	7,8
Tom Hunter	Sandia National Laboratories	Ph.D. Nuclear Engineering University of Wisconsin (1978)	Program Management Nuclear Waste Management Nuclear Engineering	12	9	7,8
Edgar Petrie	Department of Energy/Yucca Mountain Project	B.S. Physics Brown University (1951)	Systems Engineering Project Management Design Engineering	7	33	7,8

[a]Abbreviations - DOE: Department of Energy; OCRWM: Office of Civilian Radioactive Waste Management.
[b]The numbers in this column correspond to the steps in the methodology (Figure A-1).

TABLE A-5

TECHNICAL SPECIALISTS WHO PROVIDED SUPPORT TO THE EXPERT PANELS

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience Geologic Disposal	Other
Design Support and Characterization Testing Support Group					
James Copeland	Parsons, Brinckerhoff, Quade & Douglas	E.M. Mining Engineering Colorado School of Mines (1957)	Mine Design Underground Construction Cost/Schedule Analysis	1	31
Richard Coppage	Raytheon Services Nevada	B.S. Mining Engineering Montana School of Mines (1962)	ESF Design Underground Construction Mine Safety	8	22
Ray Finley	Sandia National Laboratories	M.S. Geological Engineering University of Arizona (1986)	Geotechnical Engineering In Situ Testing Rock Mechanics	5	-
Phillip Gehner	Raytheon Services Nevada	B.S. Industrial Technology Central Missouri State University (1971)	ESF Design Engineering Design Engineering Design	4	16
Richard Greenwold	Raytheon Services Nevada	Bachelor of Architecture Oklahoma State University (1968)	Architecture Design Project Management ESF Planning	3	23
William Kennedy	Raytheon Services Nevada	B.S. Geological Engineering University of Nevada Reno (1973)	Mine Design ESF Design Repository Design	7	16
Brian Lawrence	Parsons, Brinckerhoff, Quade & Douglas	Engineer of Mines Colorado School of Mines (1969)	Mine Construction/Operation Mine Design, Planning Repository Engineering	6	16
Robert Lucero	Raytheon Services Nevada	Engineering Technician T-VI Certificate (1968)	ESF Design DOE Siting Guide Site Characterization Plan		23
Steven Beason	U.S. Bureau of Reclamation	B.S. Geology Fort Lewis College (1977)	Engineering Geology Underground Construction Explor., Design, Construction	5	15

TABLE A-5

TECHNICAL SPECIALISTS WHO PROVIDED SUPPORT TO THE EXPERT PANELS
(Concluded)

Name	Affiliation	Academic Training	Areas of Expertise and Experience	Years of Professional Experience: Geologic Disposal	Years of Professional Experience: Other
Other Support					
Art Morales	Sandia National Laboratories	M.S. Electrical Engineering New Mexico State University (1975)	Repository Requirements ESF Design Support	1	23
Joe Tillerson	Sandia National Laboratories	Ph.D. Aerospace Engineering Texas A&M University (1973)	Nuclear Repository Management Rock Mechanics Underground Design	14	4
David Dobson	Department of Energy/Yucca Mountain Project	Ph.D. Geology Stanford University (1984)	Geology Geochemistry Regulatory Compliance	4	12
Barney Lewis	U.S. Geological Survey	M.S. Geology Montana State University (1974)	Groundwater Hydrology Groundwater Chemistry	4	13
Ernest Hardin	Science Applications International Corp.	M.S. Earth Sciences Massachusetts Institute of Technology (1986)	Well-Bore Geophysics Vertical Seismic Profiling Numerical Analysis	9	4
Kurt Rautenstrauch	EG&G Energy System	Ph.D. Wildlife Management University of Arizona (1987)	Applied Ecology Desert Tortoise Endangered Species	-	10
William Glassley	Lawrence Livermore National Laboratory	Ph.D. Geochemistry University of Washington (1973)	Geochemistry of Hydrothermal Systems Rock-fluid Interaction	5	18