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A DECISION ANALYSIS OF AN EXPLORATORY STUDIES FACILITY[a]

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ABSTRACT

An Exploratory Studies Facility (ESF) is planned to support the characterization of a potential site for a high-level nuclear waste repository at Yucca Mountain, NV. The selection of a design for the ESF is a critical decision, because the ESF design may affect the accuracy of characterization testing and subsequent repository design. To assist the design process, a comparative evaluation was conducted to rank 34 alternative ESF-repository designs. The evaluation relied on techniques from formal decision analysis, including decision trees and multiattribute utility analysis (MUA). The results helped to identify favorable design features and convinced the Department of Energy to adopt the top-ranked option as the preferred ESF design.

I. INTRODUCTION AND BACKGROUND

The Department of Energy (DOE) has responsibility for siting, constructing, and operating a mined geologic repository for disposing of spent nuclear fuel and other high-level radioactive waste. A site at Yucca Mountain, Nevada, has been tentatively identified as a potential location for the repository. To investigate the suitability of this site, a multi-year exploratory program, termed site characterization, is to be conducted. A critical decision for the characterization program is to select a design — including a location, mining method, and testing strategy — for the underground test facility central to the characterization effort. This facility is known as the Exploratory Studies Facility (ESF).

DOE proposed a preliminary design for the ESF and repository in its Site Characterization Plan (SCP).[1] The SCP design was, however, criticized by the U.S. Nuclear Regulatory Commission (NRC), the agency that will ultimately be asked to grant a license to construct and operate the repository, and by the Nuclear Waste Technology Review Board (NWTRB),[2] an independent oversight committee.

To respond to these criticisms, Sandia National Laboratories conducted the Exploratory Studies Facility Alternatives Study (ESF-AS), a comparative evaluation of alternative ESF-repository designs.[3] The analysis evaluated and ranked 34 options. The purpose of the analysis was to provide either (1) evidence that the SCP design was a relatively good one or (2) a basis for developing an improved design. This paper describes the analysis and summarizes the results.

II. OPTIONS EVALUATED

The decision to select an ESF design must account for the impact of that design on the potential repository. The repository must be designed around ESF excavations, so the location and methods of access selected for the ESF affect subsequent repository design choices. For the purposes of the analysis, therefore, an option was defined to consist of an ESF design plus a specified, compatible repository design.

Figure 1 illustrates key elements of the SCP ESF-repository design. The emplacement drifts and main test level (MTL) would be mined, using conventional drill-and-blast methods, in a rock formation known as the Topopah Springs (TS) unit (upper level in Figure 1). Exploratory drifts would be mined in the Calico Hills rock formation (CH unit), which lies directly below the repository and is expected to provide a barrier to the transport of radionuclides by groundwater. The SCP design calls for six accesses — two 12'-diameter shafts to provide access to the ESF, two ramps for transporting mined rock and radioactive waste, and two additional shafts to provide ventilation and transport of personnel and materials. Exploratory drifts would be mined to intercept potentially important geologic features, including the Ghost Dance Fault, and Drill Hole Wash Fault, and imbricate faults.

The SCP ESF-repository option was designated Option 1 for the analysis. To generate additional options, previously proposed designs for the ESF and repository were considered along with new designs based on recommended revisions to the SCP design. The additional options, designated Option 2 through Option 34, were chosen to provide distinct alternatives for each of the following questions:

- How many ramps and/or shafts should be planned for repository development and operation and which should be initially constructed for the ESF?
- Where should these accesses be located?

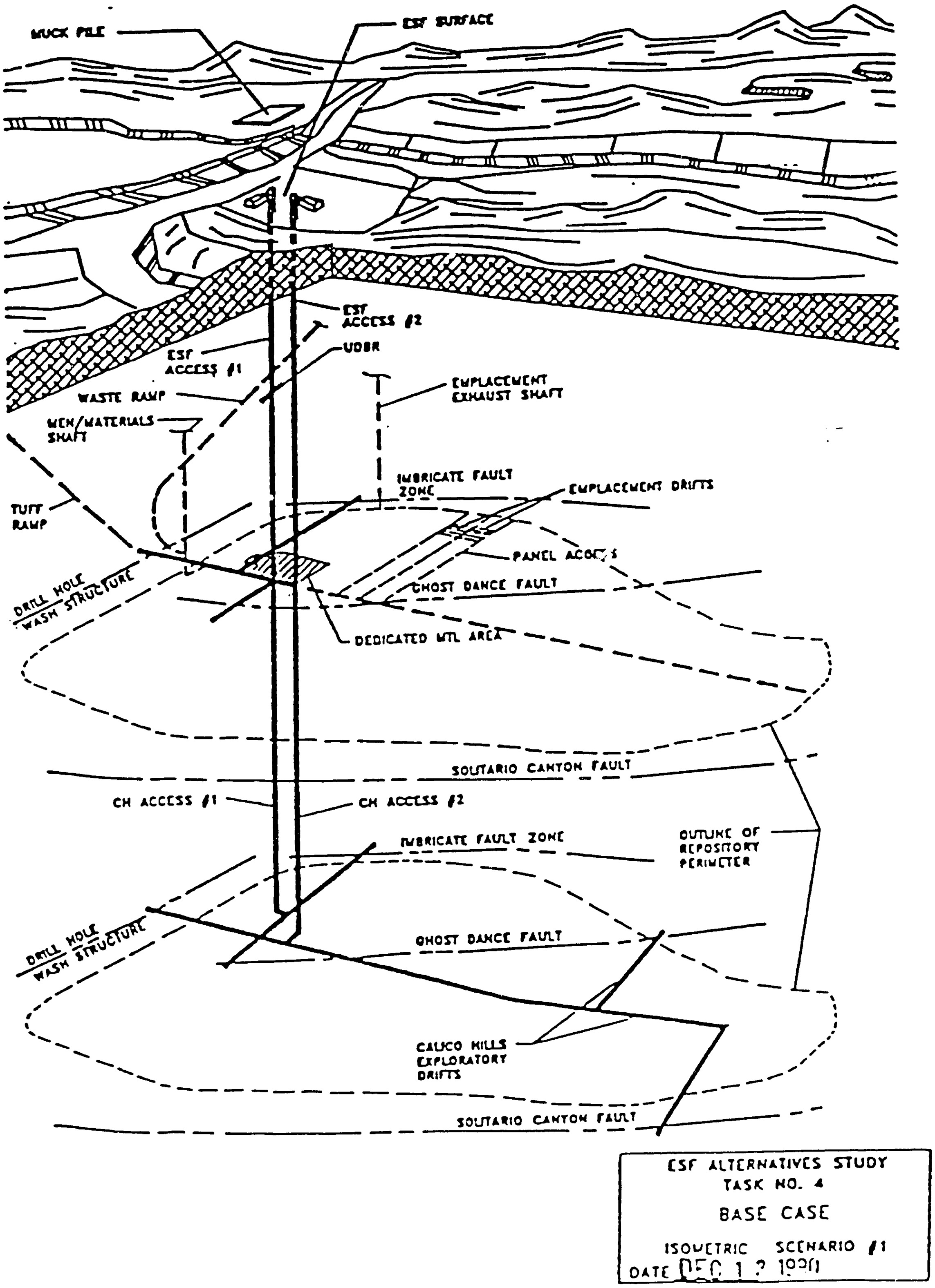

Fig. 1. Underground Layout for Option 1 – Base Case

- What underground areas should be used for testing conducted as part of the ESF, including accesses, the MTL, and mining drifts constructed to explore specific geologic features?

- What mining method should be used (e.g., conventional drill-and-blast methods or machine excavation methods)

- Should the testing strategy be optimized to achieve early access to (and therefore, rapid understanding of) the TS unit, or to achieve early access to the CH unit?

III. ANALYSIS

The evaluation was based on formal decision analysis.[4,5] The approach consisted of constructing, quantifying, and solving the decision tree shown in Figure 2.

The various paths through the decision tree represent alternative scenarios that may follow the selection of an ESF design. The uncertain events and future decisions represented in the tree include (1) the ability to maintain the viability of the repository program, (2) the outcomes of near-term and long-term characterization testing, (3) the decision on regulatory authorization for construction and operation of the repository, and (4) the decision to close the repository or to retrieve the emplaced waste. For example, one path through the tree, labeled A, represents the scenario wherein the program would remain viable, characterization testing would be successful, regulatory approvals would be obtained, the repository would be constructed, waste would be emplaced, and the repository would be closed. The other paths through the tree represent scenarios wherein the Yucca Mountain site would be abandoned because of a failure of programmatic viability, negative testing results, failure to obtain necessary regulatory approvals, or the need to retrieve waste.

Quantifying the decision tree required estimating the probabilities of the uncertain events shown in the tree and obtaining estimates of the

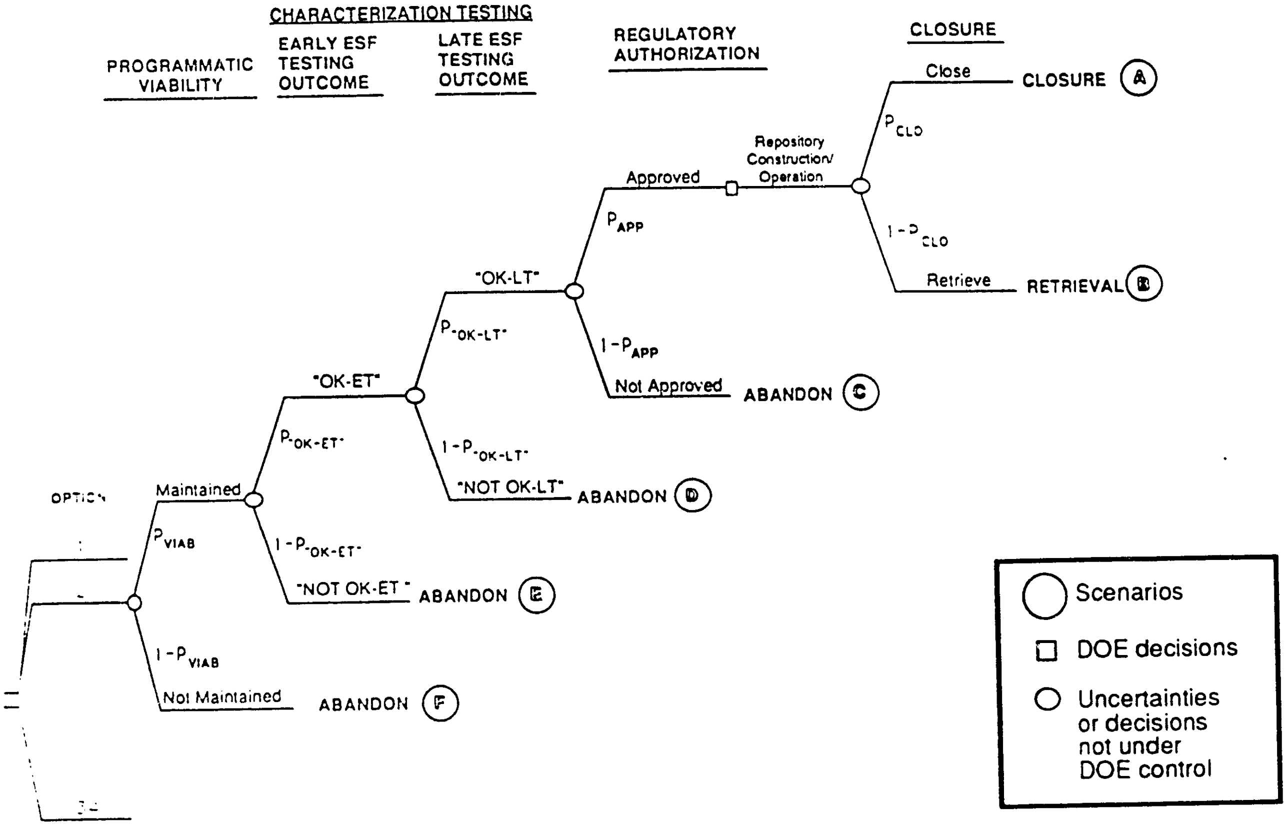

Fig. 2. Decision Tree for Evaluating ESF Options

health, safety, environmental, cost, and other consequences associated with each path through the tree as a function of the chosen ESF-repository option. Expert panels were established and analyses were conducted to develop the various probability and consequence estimates. Panel discussions were formally recorded by a court reporter. Confidence intervals were estimated to indicate the uncertainty in each estimate.

Probabilities

Probabilities were obtained as consensus, judgmental probabilities estimated by the expert panels. To support each probability estimate, the panel responsible for the estimate developed an influence diagram.[6] The influence diagram summarized 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 used to generate 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 SCP design) was estimated to perform with respect to that factor. The various comparative evaluations were aggregated, across factors and across panel members, to obtain a single, qualitative ranking of the options that accounted for all factors in the relevant influence diagram. The panel then discussed and modified this initial ranking based on the issues and considerations raised by the discussion. The final qualitative ranking was used as input for the assessment of quantitative probabilities. Panel members were trained in probability estimation and formal probability encoding techniques were used to elicit consensus probabilities.[7,8]

In the case of testing outcome probabilities, a Bayesian analysis was conducted to account for the influence of the ESF-repository option on the accuracy of tests. Figure 3 illustrates the probability tree, termed "Nature's Tree," constructed for the Bayesian analysis. The true state of the site was considered uncertain, with alternative possibilities defined in terms of the Environmental Protection Agency (EPA) standard that specifies a limit for the cumulative radionuclide releases from a repository to the accessible environment:[9]

- OK--The site was defined to be OK if the characteristics and conditions at the site 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 U.S. Environmental Protection Agency release limits for 10,000 years after closure.
- NOT OK --Conversely, the site was defined to be NOT OK if the repository system would not meet the EPA release limits.

The outcome of testing was assumed to be an indication of whether the site is OK (denoted "OK") or NOT OK (denoted "NOT OK"). The quotation marks distinguish the outcome of the test (denoted by the quotes) from the reality (no quotes). As illustrated, Nature's Tree includes the possibility of "OK" results from testing even if the site is in reality NOT OK (a false positive outcome). Similarly, the tree allows for the possibility of a "NOT OK" result from testing even if the site is, in reality, OK (a false negative outcome).

Bayes' Theorem[4], was used to update prior probabilities that the site is OK (P_{OK} in Figure 3) to produce posterior probabilities that account for the testing outcomes ($P_{\text{"OK-ET"}}$ and $P_{\text{"OK-LT"}}$ in Figure 1). Prior probabilities for whether or not the site is OK were obtained from a panel composed of experts on postclosure releases, while false positive and false negative testing outcome probabilities were obtained from a panel composed of experts on testing. The details of the Bayesian analysis are described in Boyle et al.[10]

Consequence Estimates

Table 1 lists the consequence estimates generated for the decision tree. The measures used and methods relied upon depended on the availability of applicable data and analyses. For example, postclosure releases were measured as a fraction or multiple of the limit established in the EPA Standard.[9,b] Release estimates were

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[b] 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

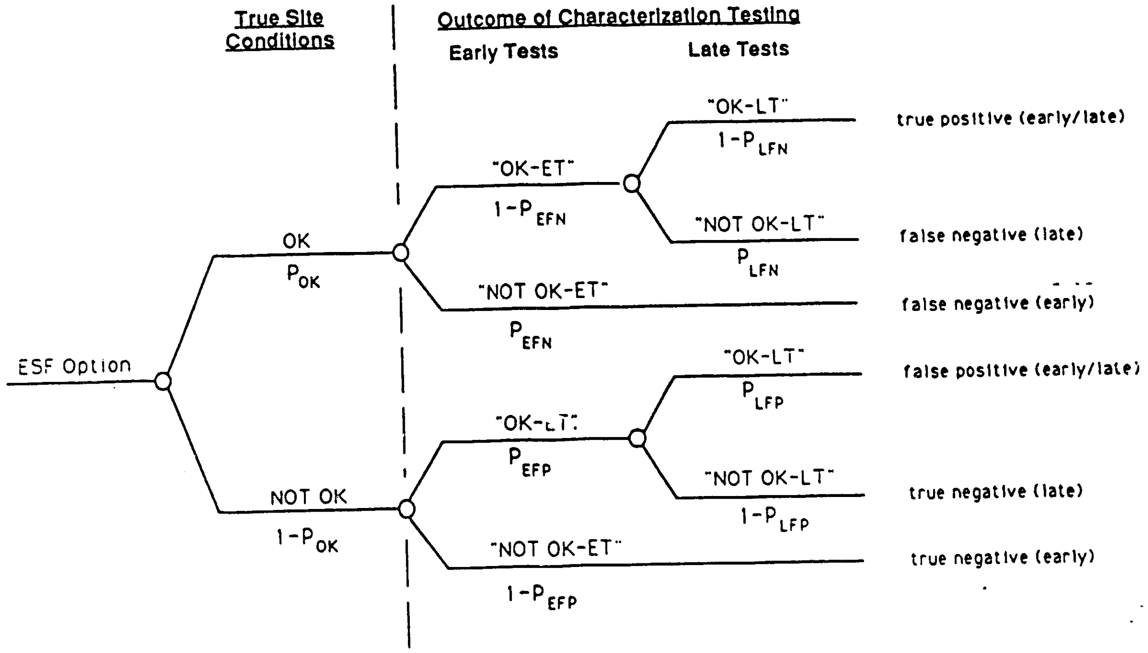

Fig. 3. Nature's Tree

developed by the expert panel on postclosure releases, based on existing estimates for aqueous and gaseous releases modified to account for the specific characteristics of the ESF-repository options. Worker non-radiological fatalities were derived using fatality data from the mining industry and the estimated number of worker-hours for the specified construction methods. Aesthetic impacts, intended to measure the degree to which the ESF and repository activities degrade local scenic quality, were measured on a constructed scale (Table 2). Sketches illustrating the surface appearance for the various options were developed to provide a means for scoring options using the constructed scale.

Appropriate consequence estimates were derived for each of the six paths through the decision tree. For example, postclosure releases were estimated only for the closure scenario (A), because only this scenario results in a closed repository. In addition, a benefit, arbitrarily assumed equal to $50 billion, was assigned to the closure scenario to account for the benefit of obtaining a closed functioning repository.

Table 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	Indirect costs	X_8	millions of discounted dollars

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mixture by the limit specified in the table and summing the results.

Table 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

Multiattribute Utility Analysis

Quantifying the decision tree also involved developing a multiattribute utility function for combining a scenario's various consequence measures into an overall measure of the desirability, termed utility, of that scenario. The value judgments necessary for constructing the utility function, including relative weights, were provided by a panel of senior managers familiar with the repository program.

The probability and utility numbers developed for the decision tree indicate how likely and desirable each scenario was judged to be. The decision tree was "solved" by computing its expected utility, weighting the utilities of each scenario by the probability of the scenario and adding the results. The options were then ranked according to expected utility (utility weighted by probability). Sensitivity analyses were conducted to identify the uncertainties in consequence and probabilities that have the greatest impact on ranking results.

III. RESULTS

Considerable uncertainties exist over the probabilities and consequence estimates as indicated by the confidence intervals provided by the expert panels. As such, the precise expected utility estimates and detailed rankings resulting from the evaluation cannot be accepted with absolute certainty. Indeed, in several cases, members of a panel could not reach a consensus, and minority opinions were reported. Nevertheless, sensitivity analyses indicated that the ranking based on best-judgment, majority opinions, was surprisingly robust. In particular, six options were found to be at the top, or near the top, of the ranking for most of the sensitivity studies. The ranking of options was completely insensitive to the benefit assumed to be associated with a closed, functioning repository, provided that the benefit is large enough to justify the repository (i.e., at least as large as the equivalent economic costs of the adverse consequences). Option 1, the original SCP design, was ranked relatively low.

Option 30 was identified as most preferred, according to the assumptions of the analysis. Unlike the SCP option, Option 30 would contain four accesses — two 25' ramps accessing a relatively large MTL in the southern corner of the repository block and two 25'-diameter mechanically mined shafts, one for materials in the south and one mechanically mined emplacement exhaust shaft in the north. There would be no direct gravity flow pathway from the TS unit to the CH unit. The testing strategy would emphasize early access to and understanding of the CH unit.

Option 30 was estimated to be superior to Option 1 with respect to all probability estimates plus the consequence estimates related to postclosure releases and impacts on historical properties. Compared to Option 1, Option 30 was estimated to have a much higher probability of maintaining near-term programmatic viability (due to its responsiveness to concerns expressed by the NWTRB and NRC), slightly better testing probabilities (due to lower false negative and false positive testing outcomes), higher probability of obtaining regulatory approvals, and lower probability of requiring waste retrieval.

The rank order of options was determined almost entirely by the relative likelihood of obtaining a closed repository. In other words, there were few differences in technical performance, with all options judged to provide acceptable performance (e.g., 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 threat, apparently, is not that a chosen ESF-repository design might fail to perform well, but that the selected design will fail to generate sufficient political and technical consensus to allow development of the repository.

The analysis generated numerous insights regarding favorable characteristics and features of an ESF-repository option. Examples of favorable features include:

- Exploratory drifting to intercept the Ghost Dance Fault in the TS unit at more than one location and to expose yet undiscovered north-south trending faults
- Flexibility for locating a large, dedicated MTL
- Minimization of the total number of accesses with at least one ramp access for the ESF
- Mechanical mining methods
- Exposure of large amounts of rock, both on and off the main block
- Maximization of the distance between waste emplacement areas and the water table
- Avoidance of emplacement drifts that cross the Ghost Dance Fault and no constructed pathways for gravity flow from the TS unit to the CH unit
- Early site-suitability tests and capability for extended duration tests and high-level waste tests.

The results of this analysis were presented to the Director of the DOE Office of Civilian Radioactive Waste Management in February, 1991. Subsequently, DOE selected Option 30, the highest-ranked option, as a recommended ESF design for further development within the repository program.

REFERENCES

1. DOE (U.S. Department of Energy), 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) (1988).

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

3. M. W. MERKHOFER, P. BECCUE, P. GNIRK, D. K. PARRISH, and W. J. BOYLE, *Exploratory Studies Facility Alternatives Study Final Report*, prepared for Sandia National Laboratories, Albuquerque, NM, SAND91-0025, Vol. 2 (June, 1991).

4. D. W. BUNN, *Applied Decision Analysis*, McGraw-Hill, New York (1984).

5. R. L. KEENEY and H. RAIFFA, *Decisions with Multiple Objectives*, John Wiley and Sons, New York (1976).

6. M. W. MERKHOFER, "Using Influence Diagrams in Multiattribute Utility Analysis -- Improving Effectiveness Through Improving Communication," Chapter 13 (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, May 9-11, 1988, University of California, Berkeley], John Wiley & Sons, London and New York (1990).

7. C. S. SPETZLER and C.-A. STAEL VON HOLSTEIN, "Probability Encoding in Decision Analysis," Management Science 22, 340-358 (November 1975).

8. M. W. MERKHOFER, "Quantifying Judgmental Uncertainty: Methodology, Experiences, and Insights," IEEE Transactions on

Systems, Man and Cybernetics SMC-17, No. 5, 741-752 (September/October 1987).

9. EPA (U.S. Environmental Protection Agency), "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 (1987).

10. W. J. BOYLE, D. K. PARRISH, and P. C. BECCUE, "Quantification of Uncertain Outcomes from Site Characterization: Insights from the ESF-AS," [this conference], 1992.

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