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Decision Analysis

A Multiattribute Utility Analysis of Alternative Sites for the Disposal of Nuclear Waste

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Five potential sites nominated for the Nation's first geologic repository for disposing of nuclear waste are evaluated using multiattribute utility analysis. The analysis was designed to aid the Department of Energy in its selection of 3 sites for characterization, a detailed data-gathering process that will involve the construction of exploratory shafts for underground testing and that may cost as much as $1 billion per site. The analysis produced insights into the relative advantages and disadvantages of the nominated sites and clarified current uncertainties regarding repository performance.

KEY WORDS: Decision analysis; multiattribute utility analysis; nuclear waste; repository siting.

1. INTRODUCTION

From the fall of 1985 to the spring of 1986, the Department of Energy (DOE) conducted a comparative evaluation[(1)] of 5 sites for permanently disposing of spent nuclear fuel and other high-level radioactive waste. The comparison was based on the principles of decision analysis and relied on the approach known as multiattribute utility analysis (MUA). This paper summarizes the MUA method used by DOE, presents the results of its application, and offers some observations on the role of the analysis in the decision-making process.

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1.1. Background

Since the mid-1970s, DOE and its predecessor agency, the Energy Research and Development Administration, have collected data on possible sites for constructing one or more underground facilities for safely disposing of nuclear waste. The waste disposal facility, known as a mined geologic repository, will consist of a system of tunnels and rooms excavated in stable rock formations at least 1,000 feet below ground. Nuclear waste will be shipped in casks from power plants to the repository and permanently placed in the repository rooms. When the repository is full, it will be sealed to minimize any radioactive leakage. The period of construction, operation, and sealing is referred to as "preclosure". The time following repository sealing is referred to as "postclosure".

In 1982, the siting process was formalized with the passage of the Nuclear Waste Policy Act (NWPA).

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The NWPA specified a sequence of steps and a schedule for selecting repository sites. The first major step, completed in November, 1984, was the establishment by DOE of general guidelines for the evaluation of possible repository sites.[2] These guidelines specify considerations related to the preclosure and postclosure behavior of the repository. Preclosure and postclosure guidelines are divided into: (a) system guidelines, which specify broad requirements dealing with objectives regarding public health and safety, the environment, socioeconomics, and the ease and cost of repository development; and (b) technical guidelines, which identify specific conditions that qualify or disqualify sites.

The second major step was the nomination by the Secretary of Energy of 5 sites as suitable for characterization (in-depth studies and data collection at the site, including the actual drilling of an exploratory shaft). In December, 1984, DOE published draft environmental assessments which tentatively nominated the following 5 sites as suitable for characterization: Davis Canyon (a site in bedded salt in Utah), Deaf Smith (a site in bedded salt in Texas), Richton Dome (a site in a salt dome in Mississippi), Hanford (a site in basalt in Washington), and Yucca Mountain (a site in volcanic tuff in Nevada). A common Chapter 7 in all the draft environmental assessments presented rankings of the 5 sites against the postclosure and preclosure technical siting guidelines.[3] Numerous comments on the draft selection methods were received by DOE, including a critical letter from the National Academy of Sciences (NAS) that called the methods "unsatisfactory, inadequate, undocumented, and biased."

Responding to these comments, DOE elected to conduct the more rigorous comparative evaluation of the nominated sites based on MUA methodology, and asked the National Academy of Sciences Board on Radioactive Waste Management to conduct an independent review of the MUA analysis. On May 28, 1986, DOE released the results of the analysis and the NAS review. Simultaneously, DOE announced that the Secretary of Energy had recommended (and the President had approved) Yucca Mountain, Nevada; Deaf Smith County, Texas; and Hanford, Washington, for characterization[4] a selection that disagrees with the ranking produced by the MUA analysis. This paper presents the analysis, its results, and the important insights produced and comments on its role as a decision aid.

1.2. Overview of the Analysis

DOE guidelines require that site-selection decisions be based on multiple objectives, including objectives dealing with health and safety, the environment, socioeconomics, and costs. MUA was selected as the method of analysis because it is a well-developed and proven method for evaluating options in decision situations involving multiple objectives[5-7]. As applied in this context, the basic premise of the MUA analysis is that the desirability of a site is determined by the extent to which it achieves the objectives of site selection. The specific steps in the application provide a means for quantifying the degree to which a site meets each objective and ensuring that these quantitative measures are combined in a way that is logically sound and consistent with the fundamental values of the decision makers. These 5 basic steps are:

1. Establish preclosure and postclosure objectives of repository siting and develop a performance measure for quantifying the degree to which each objective is met.
2. For the postclosure analysis, specify a set of postclosure scenarios that, should they occur, might effect the performance of the repository system.
3. Quantify the estimated preclosure performance of each site using the preclosure performance measures. For each postclosure scenario, quantify the estimated postclosure performance of each site using the postclosure performance measures.
4. Develop a quantitative model of values for combining the various performance measures to obtain an overall measure of desirability (i.e., assess a utility function).
5. Calculate preclosure, postclosure, and composite utilities (quantitative measures of site desirability) for each site. Perform sensitivity analyses to determine which technical judgments and value judgments are most critical.

A task force was established within the DOE Office of Civilian Radioactive Waste Management (OCRWM) for the purpose of conducting the analysis. The task force was composed of 3 separate groups. One group, consisting of selected DOE staff and decision analysts, was responsible for conducting the analysis. The other two groups provided the two major types of inputs required for the application of MUA: technical judgments and value judgments.

To provide technical judgments, 6 panels of technical specialists were established. Each panel was responsible for a major technical area represented in the siting guidelines. The technical specialists were selected for their familiarity with the information contained in the 5 environmental assessments and with the siting guidelines. With guidance from decision analysts, they developed the measures for quantifying performance; identified, developed, and analyzed scenarios regarding the postclosure performance of a repository; and provided judgmental estimates of the performance of each site on each performance measure.

The inputs to the analysis that deal with preferences—that is, value judgements—were provided by 4 senior DOE managers in OCRWM. This group was responsible for specifying the objectives for site selection, the value tradeoffs among objectives, and the attitude toward risks used in the analysis. Care was taken to maintain separation between technical and value judgments.

2. REPOSITORY SITE OBJECTIVES AND PERFORMANCE MEASURES

Fig. 1, illustrates a hierarchy of the preclosure objectives. Health and safety effects are divided into those due to the repository and those due to the transportation of waste. Furthermore, radiological and nonradiological health effects are separately accounted for, as are potential effects to workers and the public. The impacts to the environment of primary concern are: noise and visual impacts associated with the construction and operation of the repository; damage or disruption to archaeological, historical, and cultural properties; and adverse effects on plants and animals. Thus, the specific environmental objectives of site selection are to minimize adverse environmental impacts in each of the above areas. Cost

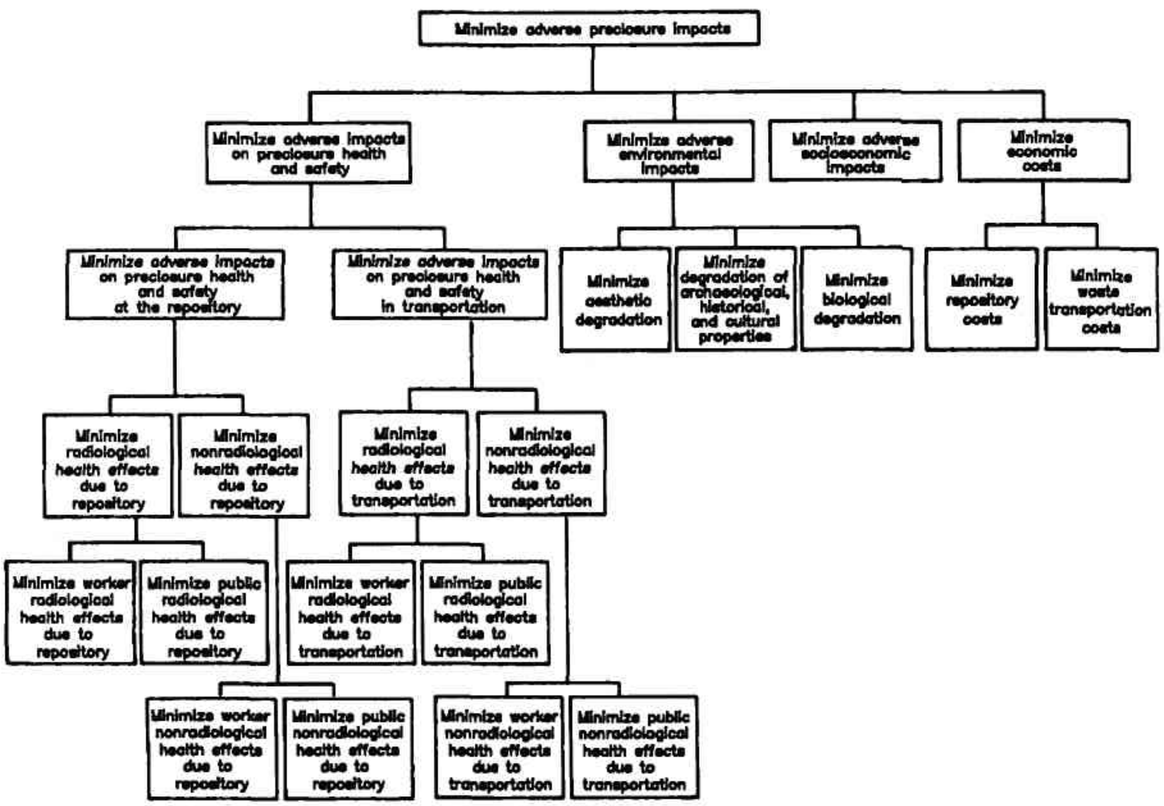

Fig. 1. Preclosure objectives hierarchy.

objectives are to minimize repository and transportation costs.

During postclosure, the primary concern is the protection of public health and safety. Regulations established by the U.S. Environmental Protection Agency (EPA) specify limits on radionuclide releases to the accessible environment during the first 10,000 years after closure. In addition, the siting guidelines call for comparisons of alternative sites for 100,000 years after closure. To account for these time periods, 2 postclosure objectives were established: (a) minimize adverse health effects attributable to the repository during the first 10,000 years after repository closure, and (b) minimize adverse health effects attributable to the repository during the period 10,000–100,000 years after repository closure.

Table I summarizes the correspondence between various objectives and their associated performance

Table I. Objectives and Performance Measures

Objective	Performance measure	Units
	Preclosure	
Health and Safety		
1. Minimize worker health effects from radiation exposure at the repository	X_1: Repository-worker radiological fatalities	Number of cancer deaths
2. Minimize public health effects from radiation exposure at the repository	X_2: Public radiological fatalities from repository	Number of cancer deaths
3. Minimize worker health effects from nonradiological causes at the repository	X_3: Repository-worker nonradiological fatalities	Number of accident deaths
4. Minimize public health effects from nonradiological causes at the repository	X_4: Public nonradiological fatalities from repository	Number of deaths attributable to air pollution
5. Minimize worker health effects from radiation exposure in waste transportation	X_5: Transportation-worker radiological fatalities	Number of cancer deaths
6. Minimize public health effects from radiation exposure in waste transportation	X_6: Public radiological fatalities from transportation	Number of cancer deaths
7. Minimize worker health effects from nonradiological causes in waste transportation	X_7: Transportation-worker nonradiological fatalities	Number of accident deaths
8. Minimize public health effects from nonradiological causes in waste transportation	X_8: Public nonradiological fatalities from transportation	Number of accident deaths
Environment		
9. Minimize adverse aesthetic impacts	X_9: Constructed scale (see Table II)	0,1,2,3,4,5,6
10. Minimize adverse archaeological, historical, and cultural impacts	X_{10}: Constructed scale (see Table III)	0,1,2,3,4,5
11. Minimize adverse biological degradation	X_{11}: Constructed scale (see Table IV)	0,1,2,3,4,5
Socioeconomics		
12. Minimize adverse socioeconomic impacts	X_{12}: Constructed scale (see Table V)	0,1,2,3,4
Costs		
13 Minimize repository costs	X_{13}: Costs	Millions of dollars
14. Minimize waste-transportation costs	X_{14}: Costs	Millions of dollars
	Postclosure	
1. Minimize the total number of health effects attributable to the repository during the first 10,000 years after repository closure	Y_1: Cumulative releases of radionuclides to the accessible environment during the first 10,000 years after repository closure	Multiples of the release limits specified by the EPA standard[8]
2. Minimize the total number of health effects attributable to the repository during the period 10,000–100,000 years after repository closure	Y_1: Cumulative releases of radionuclides to the accessible environment during the period 10,000–100,000 years after repository closure	Multiples of the release limits specified by the EPA standard[8]

Table II. Simplified Description of Performance Measure X_9 for Adverse Aesthetic Impacts from the Repository and Waste Transportation

Impact level	Aesthetic impacts in the effected area[a]
0	None
1	One minor effect
2	Two minor effects
3	Three minor effects
4	One major effect
5	Two major effects
6	Three major effects

[a] Effects occur when there are visual impacts or noise degrading an aesthetic resource (e.g., park or forest). Major effects require significant visual contact or noise levels exceeding established criteria that effect many visitors or residents. Minor effects result when the visual impacts or noise are noticeable but not significant.

measures and units. Natural scales were used wherever possible. Thus, numbers of fatalities were selected as performance measures for quantifying preclosure health and safety objectives, and expenditures (expressed in millions of dollars) was selected as the performance measure for costs. Since no convenient natural scales exist for measuring environmental and socioeconomic impacts, a performance measure for each of these objectives was constructed by defining a scale in terms of several specified, distinct levels of impact (Tables II–V). For example, a six-point scale was constructed to quantify impacts on historical properties. On this scale, level 0 was defined as the absence of impact on any significant historical properties. Level 5 was the highest level of impact corresponding to major adverse effects on several (4 or more) properties of major significance or many (20 or more) properties of minor significance.

A natural, direct measure for postclosure health effects is the number of cancer fatalities attributable to the repository. This was not selected because of the difficulty of predicting fatalities attributable to radionuclide releases from a repository. The size and geographic distribution of populations, dietary habits, medical treatment technologies, and lifestyles will change dramatically over the next centuries, yet these factors all influence the health consequences of radionuclide releases. Hence, surrogate performance measures, namely the cumulative radionuclide releases to the accessible environment expressed as a fraction of the limit allowed by the applicable EPA standard[8], were chosen for the first 10,000 years after closure and the period from 10,000–100,000 years after closure. Although the standard refers to releases occurring in the first 10,000 years only, the allowed limit was used as a unit of measure for both periods.

Table III. Simplified Description of Performance Measure X_{10} for Adverse Archaeological, Historical, and Cultural Impacts from the Repository and Waste Transportation

Impact level	Impacts on historical properties in the effected area[a]
0	There are no impacts on any significant historical properties
1	One historical property of major significance or 5 historical properties of minor significance are subjected to minimal adverse impacts
2	Two historical properties of major significance or 10 historical properties of minor significance are subjected to minimal adverse impacts
3	Two historical properties of major significance or 10 historical properties of minor significance are subjected to major adverse impacts
4	Three historical properties of major significance or 15 historical properties of minor significance are subjected to major adverse impacts
5	Four historical properties of major significance or 20 historical properties of minor significance are subjected to major adverse impacts

[a] A historical property of major significance meets the criteria for the National Register of Historic Places (e.g., first town hall in a community; cave sites representative of an Indian people at one stage of their history; a Civil War battlefield). A historical property of minor significance has local significance (e.g., a homestead or miner's cabin, an archaeological site that is representative of a period for which there are many examples). Major impacts change the integrity or significance of the historical property. Minimal impacts may alter the historical property, but will not change its integrity or its significance.

Table IV. Simplified Description of Performance Measure X_{11} for Adverse Biological Impacts from the Repository and Waste Transportation

Impact level	Biological impacts in the effected area
0	No damage to species of plants or wildlife that are desirable, unique, biologically sensitive, or endangered, or to any habitats for such species
1	Damage to individuals of desirable species or habitats for the species, but such species or habitats are common throughout the region
2	Damage to individuals of biologically sensitive species or portions of their habitats, but this does not threaten their regional abundance
3	Damage to, or destruction of, individuals of threatened and endangered (T&E) species or portions of their habitats that does not threaten their regional abundance; or sensitive species or resource areas are in the affected area, and damage to, or destruction of, individuals of these biologically sensitive species or portions of their habitats threatens their regional abundance
4	Damage to, or destruction of, individuals of T&E species or portions of their habitats that does not threaten their regional abundance; and damage to, or destruction of, individuals of biologically sensitive species or portions of their habitats that threatens their regional abundance
5	Damage to, or destruction of, individuals of T&E species or portions of their habitats that threatens their regional abundance; and damage to, or destruction of, individuals of biologically sensitive species or portions of their habitats that threatens their regional abundance

3. POSTCLOSURE SCENARIOS

Postclosure scenarios account for the possibility of undetected, unexpected conditions and disruptive processes or events occurring at each site. The postclosure scenarios that passed an initial screening process are listed in Table VI. Site-specific judgmental probabilities were assigned to quantify the likelihood of each scenario occurring within the first 10,000 years at each site (Table VII). As indicated, probabilities were not assigned if, in the judgment of the panel, the occurrence of the scenario at a site would not significantly affect the performance of the repository or if the maximum probability of the scenario was judged to be $<1/10{,}000$ over 10,000 years.

Care was taken in the assessment of probabilities as experience and experiments indicate the difficulty of accurately representing one's state of knowledge about the likelihood of complex events[9,10]. However, investigations by Murphy and Winkler[11] suggest that professionals with training in assessing probabilities can conduct this task in a reliable manner. Thus, to help avoid errors in assessed probabilities, postclosure technical panel members 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 broad range of sample questions. The probabilities estimated by each panel member were tabulated and compared with the actual answers to the sample questions. This permitted each member to test his or her skill at assessing judgmental probabilities and provided an increased awareness of the need to avoid assessment biases. Finally, procedures that have been developed to provide meaningful probability assessments were used to estimate the probabilities of the scenarios presented in the table.[12]

As can be seen from Table VII, scenario 1 (expected conditions) was viewed as the most likely scenario at all sites (96–98% of the probability in the base case). Scenario 2 (unexpected features) was judged to be the next most likely scenario for all sites, with 1.3–2.4% of the base-case probabilities. Of the disruptive scenarios, human intrusion through exploratory drilling was regarded to be most likely to occur at the salt sites. Incomplete sealing of the shafts and the repository was viewed to be more likely at the Hanford site than at the other sites. Tectonic activity of sufficient magnitude to affect the

Table V. Simplified Description of Performance Measure X_{12} for Adverse Socioeconomic Impacts from the Repository and Waste Transportation

Impact level	Sociological impacts in the effected area[a]
0	No social or local economic disruptions occur; no commercial, residential, or agricultural displacement occurs; and no adverse impacts on water resources occur
1	An in-migrating population of about 5,000 persons is dispersed over an area with a population of around 50,000; in-migrant lifestyles match those of current residents, and no major social disruptions result; disruption of existing business patterns is avoided by standard economic planning measures; no adverse impacts on water resources occur, but minimal commercial, residential, or agricultural displacement results
2	An in-migrating population of about 5,000 persons is concentrated in a few communities within an area with a population of around 50,000; major upgrading of the public infrastructure is required; twenty-five% of the residents have lifestyles and values that are unlikely to match those of in-migrants; major social disruptions do not result; disruption of existing business patterns is avoided by standard economic planning measures; minor diversion of water resources from other activities occurs; half of the land is privately owned, and commercial, residential, or agricultural displacement results
3	An in-migrating population of about 10,000 persons is concentrated in a few communities within an area with a population of around 100,000; major upgrading of the public infrastructure and considerable new housing are required; affected communities have homogeneous lifestyles and values that do not match those of the in-migrants; significant disruption to existing business patterns and substantial economic decline result after the completion of waste-emplacement operations; minor diversion of water resources from other activities occurs; all land is privately owned, and commercial, residential, or agricultural displacement results
4	An in-migrating population of about 10,000 persons is concentrated in a few communities within an area with a population of around 100,000; major upgrading of the public infrastructure and considerable new housing are required; affected communities have homogeneous lifestyles and values that do not match those of the in-migrants; significant disruption to existing business patterns and substantial economic decline result after the completion of waste-emplacement operations; major diversion of area water sources occurs, resulting in impacts on development in the affected area; all land is privately owned, and commercial, residential, or agricultural displacement results

[a] The public infrastructure includes schools; police and fire services; water, sewer, and solid-waste systems; and recreation facilities.

performance of the repository was judged most likely at the Hanford site. A volcanic (magnatic) event of sufficient magnitude to affect the expected performance of the repository was judged most likely at the Yucca Mountain site.

4. ESTIMATED PERFORMANCE OF EACH REPOSITORY SITE

Estimates of the preclosure and postclosure performance of a repository at each site were generated by the 6 panels of technical specialists, with each panel addressing all 5 sites and having responsibility for estimating those site impacts within its members' areas of primary expertise. In each case, the ranges were determined with the intent that they would have a 90% probability of encompassing the actual impacts due to a repository at the site. Details of the process used to generate estimates of site impacts varied from panel to panel. Where available, well-established analytical models were used to obtain many of the estimates of impacts. For example, base-case estimates for the 4 preclosure performance measures characterizing the effects of transportation on health and safety were generated from a computer model involving assumptions for the fraction of waste transported by truck vs. rail, estimates of emitted radiation, exposed population densities, and the rates of train and truck accidents[13,14]. Table VIII sum-

Table VI. Potentially Significant Scenarios

Scenario	Description
1	Expected conditions (based on available information)
2	Unexpected features
3	Repository-induced dissolution of the host rock
4	Advance of a dissolution front
5	Movement on a large fault inside the controlled area but outside the repository
6	Movement on a large fault within the repository
7	Movement on a small fault inside the controlled area but outside the repository
8	Movement on a small fault within the repository
9	Movement on a large fault outside the controlled area
10a	Extrusive magmatic event that occurs during the first 500 years after closure
10b	Extrusive magmatic event that occurs 500 to 10,000 years after closure
11	Intrusive magmatic event
12	Large-scale exploratory drilling
13	Small-scale exploratory drilling
14	Incomplete sealing of the shafts and the repository

marizes the base-case estimates and ranges produced by the preclosure panels for each site and each of the 14 preclosure performance measures.

Estimating postclosure impacts was more difficult, due to the complex relationship between a site's geohydrologic characteristics and the long-term releases from a repository, and the need to generate separate estimates for each postclosure scenario. To simplify the process, members of the postclosure technical panel most familiar with the mechanisms of radionuclide release and transport constructed the scale shown in Fig. 2. A similar scale was constructed for the second postclosure period. Using these scales, the results of available computer simulations, and some auxiliary calculations, panel members generated Table IX. The table shows, for each scenario and site, the base-case estimates and uncertainty ranges for postclosure releases.

5. STRUCTURING THE MULTIATTRIBUTE UTILITY FUNCTION

Aggregating the various impact estimates to obtain an overall measure of the desirability of each site requires 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. To develop an appropriate functional form for the utility function, it is necessary to determine the degree and nature of independence among performance measures[15,16]. Various independence checks were used to verify an additive form. Specifically, the overall utility function U is:

$$U(x_1,\ldots,x_{14};y_1,y_2)=k_{\text{pre}}U_{\text{pre}}(x_1,\ldots,x_{14}) + k_{\text{post}}U_{\text{post}}(y_1,y_2), \quad (1)$$

where k_{pre} and k_{post} are positive scaling factors that sum to 1; U_{pre} and U_{post} are preclosure and postclosure multiattribute utility functions; and U, U_{pre}, and U_{post} are scaled from 0–100. The preclosure multiattribute utility function has the additive form:

$$U_{\text{pre}}(x_1,\ldots,x_{14})=121-0.05\sum_{i=1}^{14}K_iC_i(x_i) \quad (2)$$

where the C_i terms are component disutility functions for performance measures X_i, $i=1,\ldots,14$, the K_i terms are positive scaling factors representing value tradeoffs between units of the corresponding performance measure and repository costs, and the

Table VII. High, Base-Case, and Low Probabilities Assessed for Scenario[a]

Scenario[b]	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mountain
1[c]	1	1	1	1	1
	0.8×10^{-1}	0.8×10^{-1}	0.8×10^{-1}	0.6×10^{-1}	0.8×10^{-1}
	8.0×10^{-1}	8.0×10^{-1}	8.0×10^{-1}	6.4×10^{-1}	8.0×10^{-1}
2	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	2.5×10^{-1}	2.0×10^{-1}
	1.4×10^{-2}	1.6×10^{-2}	1.3×10^{-2}	2.4×10^{-2}	1.0×10^{-2}
	0	0	0	0	0
3	NC	NC	NC	NC	NC
4	NC	NC	NC	NC	NC
5	NC	NC	NC	1.0×10^{-2}	NA
				3.2×10^{-3}	
				1.0×10^{-5}	
6	NC	NC	NC	3.2×10^{-4}	NA
				3.2×10^{-4}	
				3.0×10^{-5}	
7	NA	NA	NC	NA	NA
8	NC	NC	NC	NA	NA
9	NA	NA	NA	NA	NA
10a	NC	NC	NC	NC	5.0×10^{-6}
					5.0×10^{-8}
					1.0×10^{-10}
10b	NC	NC	NC	NC	1.0×10^{-4}
					1.0×10^{-6}
					1.0×10^{-10}
11	NC	NC	NC	NC	NC
12	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	NC	NC
	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}		
	1.0×10^{-5}	1.0×10^{-5}	1.0×10^{-5}		
13	NA	NA	NA	NA	NA
14	1.0×10^{-3}	2.0×10^{-3}	5.0×10^{-3}	1.0×10^{-1}	NC
	1.0×10^{-4}	2.0×10^{-4}	5.0×10^{-4}	1.0×10^{-2}	
	1.0×10^{-5}	1.0×10^{-5}	1.0×10^{-5}	1.0×10^{-3}	

[a] Key: NA, scenario judged to have an insignificant effect on releases; NC, scenario judged to be extremely unlikely.

[b] See Table VI for descriptions.

[c] The high probability for scenario 1 is equal to 1 minus the sum of the low probabilities of scenarios 2 through 14. The low probability for scenario 1 is equal to 1 minus the sum of the high probabilities of scenarios 2 through 14. The probabilities listed for scenario 1 are rounded off.

factors 121 and -0.05 are necessary to scale the preclosure utility from 0–100. Table X shows the ranges of the performance measures, which were chosen to be broad enough to include all possible levels of impacts estimated for all of the nominated sites. The scaling of the preclosure utility function is such that utilities of 0 and 100 are assigned to the sets of impacts respectively represented by the highest and the lowest levels of the impact ranges. Table X also presents base-case estimates of K_i and C_i calculated from value judgments elicited from 4 senior managers in the OCRWM.

To interpret the values of C_i and K_i in Table X, some examples are helpful. Assessed value judgments indicated that disutility should be proportional to the number of worker cancer deaths. Thus, the component disutility function C_1 for worker radiological fatalities from the repository is simply x_1, the number of cancer deaths. For aesthetic impacts, the component disutility function C_9 represents the percentage of the highest level of aesthetic impact described in Table II. The highest level is level 6, so $C_9(6)=100$. Since $C_9(4)=33$, as shown in Table X, aesthetic impacts of level 4 were judged to be one

Table VIII. Base-Case Estimates and Ranges of Preclosure Site Impacts[a]

Performance measure	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mountain
X_1, Repository-worker radiological fatalities	2 (1–4)	2 (1–4)	2 (1–4)	9 (2–17)	4 (1–9)
X_2, Public radiological fatalities from repository	< 0.1 (< 0.1–0.2)	0.5 (0.1–1)	0.7 (0.3–1.5)	0.7 (< 0.1–1.5)	0.1 (< 0.1–0.1)
X_3, Repository-worker nonradiological fatalities	27 (17–36)	29 (19–39)	27 (17–36)	43 (28–58)	18 (12–24)
X_4, Public nonradiological fatalities from repository	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)
X_5, Transportation-worker radiological fatalities	0.73 (0–1.0)	0.64 (0–0.90)	0.52 (0–0.73)	0.9 (0–1.3)	0.81 (0–1.1)
X_6, Public radiological fatalities from transportation	3.5 (0–4.9)	2.9 (0–4.1)	2.4 (0–3.4)	4.3 (0–6.1)	4.1 (0–5.7)
X_7, Transportation-worker nonradiological fatalities	2.1 (0.96–3.4)	1.6 (0.73–2.6)	1.3 (0.6–2.1)	2.7 (1.2–4.3)	2.5 (1.1–4.0)
X_8, Public nonradiological fatalities from transportation	8.4 (3.9–13.5)	6.7 (3.1–10.8)	5.3 (2.4–8.5)	11.0 (5–17.7)	10.2 (4.7–16.4)
X_9, Aesthetic impacts (see Table II)	6 (6–6)	4 (3–5)	4 (1–5)	1 (1–2)	4 (1–5)
X_{10}, Archaeological, historical, and cultural impacts (see Table III)	3 (2.5–5)	1 (0–2.5)	0.5 (0–1)	0.5 (0.5–3)	2 (2–3.5)
X_{11}, Biological impacts (see Table IV)	3.5 (2.67–4.5)	2.33 (1.5–3)	2.67 (2–3.5)	2.33 (1–3.5)	2 (1–2.67)
X_{12}, Socioeconomic impacts (see Table V)	2 (1.33–3)	1.67 (1–3)	2 (1–3)	0.33 (0–0.67)	0.67 (0.33–2)
X_{13}, Repository cost (millions of dollars)	10,400 (6760–14,040)	9,500 (6175–12,825)	9,000 (5850–12,150)	12,900 (8385–17,415)	7,500 (4875–10,125)
X_{14}, Transportation cost (millions of dollars)	1,240 (330–2600)	1,120 (300–2350)	970 (260–2040)	1,450 (390–3040)	1,400 (380–2940)

[a] Ranges are given in parentheses; lower levels of impact are more preferred than higher levels.

third as undesirable as impacts of level 6 (i.e., 33 is one third of 100).

The value tradeoff K_8 is 4. This means that for the purposes of comparing the sites, the policy judgment was made that the impact of one additional statistical public fatality due to a transportation accident was just as undesirable as an additional $4 million in construction costs. It should be noted that the value tradeoffs for all of the performance measures dealing with health and safety apply to statistical changes in the number of deaths only. They do not imply a judgment that an identified human life is "worth" the indicated amount of money.

The value tradeoff $K_9 = 1$ means that the impact of an additional 1% of aesthetic degradation is deemed as undesirable as an additional cost of $1 million. The value tradeoff $K_{14} = 1$ means that a $1 million in transportation cost is deemed equivalent to a $1 million in repository cost. That $K_{13} = 1$ is by definition.

The postclosure utility function has the additive form:

$$U_{\text{post}}(y_1, y_2) = 100[k_1U_1(y_1) + k_2U_2(y_2)] \quad (3)$$

where U_1 and U_2 are component utility functions for performance measures Y_1 and Y_2, k_1 and k_2 are scaling factors used to account for the value tradeoff of performance in the 2 postclosure time periods. Table XI indicates the ranges of possible impacts and base-case values for the scaling factors and component utility functions calculated from value judgments elicited from OCRWM managers. The value judgments indicate that incremental utility is proportional to decreases in releases. The OCRWM managers felt approximately indifferent between a fixed rate of radionuclide release occurring in either of the two postclosure time periods, and this judgment was used to compute the base-case scaling factors. A sensitivity analysis, however, was con-

PERFORMANCE MEASURE—Cumulative Releases of Radionuclides to the Accessible Environment During the First 10,000 Years After Repository Closure

Cumulative Releases Over the First 10,000 Years as Multiples of the EPA Release Limits	Characteristics of the Site for Which the Cumulative Releases on the Left Are Judged To Be Reasonable
0.0001	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are insignificant. This judgment is based on a combination of site characteristics that implies an extremely limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 1 percent of the EPA release limits because of an extremely low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that very strongly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 200,000 years because of extremely favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with an extremely long ground-water travel time.
0.001	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are extremely small. This judgment is based on a combination of site characteristics that implies a very limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 3 percent of the EPA release limits because of an extremely low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that strongly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 150,000 years because of extremely favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with an extremely long ground-water travel time.
0.01	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are very small. This judgment is based on a combination of site characteristics that implies a limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 10 percent of the EPA release limits because of a very low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 100,000 years because of very favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a very long ground-water travel time.
0.1	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are small. This judgment is based on a combination of site characteristics that implies some potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 30 percent of the EPA release limits because of a low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 50,000 years because of favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a long ground-water travel time.
1	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are significant. This judgment is based on a combination of site characteristics that implies high potential for releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 100 percent of the EPA release limits because of a high volumetric flow rate of ground water across or through the host rock together with geochemical ground water conditions that weakly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is less than 10,000 years because of moderate retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a moderate ground-water travel time.
10	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are extremely significant. This judgment is based on a combination of site characteristics that implies an extremely high potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 1000 percent of the EPA release limits because of an extremely high volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that enhance waste dissolution. • The median travel time to the accessible environment of any key radionuclide is less than 3000 years because of little retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a short ground-water travel time.

NOTE: It must be kept in mind that the set of site characteristics that leads to any given score is not unique.

Fig. 2. Scale used to aid the judgmental estimation of releases during the first 10,000 years after repository closure.

Table IX. Base-Case Postclosure Release Estimates and Ranges for Significant Scenarios[a, b]

Scenario[c]	Davis Canyon Y_1 0–10[d]	Davis Canyon Y_2 10–100	Deaf Smith Y_1 0–10	Deaf Smith Y_2 10–100	Richton Dome Y_1 0–10	Richton Dome Y_2 10–100	Hanford Y_1 0–10	Hanford Y_2 10–100	Yucca Mountain Y_1 0–10	Yucca Mountain Y_2 10–100
1	.0001 (<.0001–.001)	.001 (<.001–.01)	.0001 (<.0001–.001)	.003 (.001–.03)	.0001 (<.0001–.001)	.001 (<.001–.01)	.001 (.0001–.1)	.03 (.001–1)	.0001 (<.0001–.03)	.003 (.001–.3)
2	.0003 (.0001–.03)	.003 (.001–.3)	.001 (.0001–.03)	.01 (.001–.3)	.0003 (.0001–.01)	.003 (.001–.1)	.01 (.0001–1)	.1 (.001–10)	.001 (.0001–1)	.01 (.001–10)
5	NC		NC		NC		.003 (.0001–.3)	.03 (.001–3)	NA	
6	NC		NC		NC		.01 (.0003–1)	.1 (.003–10)	NA	
10a	NC		NC		NC		NC		1 (.003–10)	.03 (.003–3)
10b	NC		NC		NC		NC		.3 (.003–10)	.03 (.001–10)
12	.0003 (.0001–.01)	.003 (.001–.1)	.0003 (.0001–.01)	.003 (.001–.1)	.001 (.0001–.1)	.01 (.001–1)	NC		NC	
13	NA		NA		NA		NA		NA	
14	.0001 (<.0001–.001)	.001 (<.001–.03)	.0001 (<.0001–.003)	.003 (.001–.1)	.0001 (<.0001–.003)	.001 (<.001–.03)	.003 (.0001–.3)	.03 (.001–3)	NA	

[a] Key: NA, scenario judged to have insignificant effect on releases; NC, scenario judged to be extremely unlikely.
[b] Ranges are given in parentheses.
[c] See Table VI for descriptions.
[d] The numbers 0–10 and 10–100 represent 0–10,000 years after closure and 10,000–100,000 years after closure, respectively.

Table X. Parameters in the Base-Case Preclosure Multiattribute Utility Function and Equivalent-Consequence Function

	Impact range		Utility function components	
Performance measure	Lowest level	Highest level	Value tradeoff, K_i	Component disutility functions, C_i
X_1, Repository-worker radiological fatalities	0	30	1	x_1
X_2, Public radiological fatalities from repository	0	10	4	x_2
X_3, Repository-worker nonradiological fatalities	0	100	1	x_3
X_4, Public nonradiological fatalities from repository	0	10	4	x_4
X_5, Transportation-worker radiological fatalities	0	10	1	x_5
X_6, Public radiological fatalities from transportation	0	10	4	x_6
X_7, Transportation-worker nonradiological fatalities	0	10	1	x_7
X_8, Public nonradiological fatalities from transportation	0	20	4	x_8
X_9, Aesthetic impacts (see Table II)	0	6	1	$C_9(0) = 0$, $C_9(1) = 3$, $C_9(2) = 6$, $C_9(3) = 9$, $C_9(4) = 33$, $C_9(5) = 67$, $C_9(6) = 100$
X_{10}, Archaeological, historical, and cultural impacts (see Table III)	0	5	0.2	$C_{10}(0) = 0$, $C_{10}(1) = 12$, $C_{10}(2) = 23$, $C_{10}(3) = 56$, $C_{10}(4) = 78$, $C{:}_{10}(5) = 100$
X_{11}, Biological impacts (see Table IV)	0	5	0.3	$C_{11}(0) =$, $C_{11}(1) = 4$, $C_{11}(2) = 10$, $C_{11}(3) = 18$, $C_{11}(4) = 40$, $C_{11}(5) = 100$
X_{12}, Socioeconomic impacts (see Table V)	0	4	5	$C_{12}(0) = 0$, $C_{12}(1) = 8$, $C_{12}(2) = 20$, $C_{12}(3) = 60$, $C_{12}(4) = 100$
X_{13}, Repository cost (millions of dollars)	4,000	19,000	1	x_{13}
X_{14}, Transportation cost (millions of dollars	200	4,200	1	x_{14}

Table XI. Parameters in the Base-Case Postclosure Multiattribute Utility Function

		Impact range		Utility function components	
	Performance measure	Lowest level	Highest level	Value tradeoff	Component utility functions
Y_1,	Cumulative releases of radionuclides to the accessible environment during the first 10,000 years after repository closure expressed as a fraction of the EPA limits	0	10	$k_1 = 0.53$	$U_1 = 1 - y_1$
Y_2,	Cumulative releases of radionuclides to the accessible environment during the period 10,000–100,000 years after repository closure expressed as a fraction of the EPA limits	0	100	$k_2 = 0.47$	$U_2 = 1 - \frac{y_2}{9}$

ducted over the entire range of possible postclosure scaling factors. It may be computed from the values given in Table XI and Eq. (3) that a site producing releases at the limit allowed by the EPA standard during the first 10,000 years (i.e., $y_1 = 1$) and at this same rate in the next 90,000-year interval (i.e., $y_2 = 9$) has a postclosure utility of zero.

6. SITE EVALUATION AND SENSITIVITY ANALYSIS

Insights into the strengths and weaknesses of the sites may be obtained if the sites' postclosure and preclosure utilities are individually analyzed. Therefore, before describing the overall, composite measures of site performance, preclosure and postclosure results are presented.

6.1. Preclosure Results

In the case of preclosure, the only variable term in the preclosure multiattribute utility function Eq. (2) is:

$$C(x_1, x_2, \ldots, x_{14}) = \sum_{i=1}^{14} K_i C_i(x_i) \tag{4}$$

where C may be interpreted as an equivalent-consequence function for the preclosure impacts of a repository. Using Eq. (4), equivalent consequences can be aggregated for various subsets of the estimated preclosure impacts. The measure C has the property that higher numbers are less desirable and its unit may be interpreted as an equivalent monetary cost expressed in millions of dollars. Table XII presents the equivalent monetary costs calculated for various subsets of the preclosure performance measures and the preclosure utility of each site. Some of the conclusions derived from examining the various rows of the table are presented in the paragraphs that follow.

Row 4 indicates that the ranking of sites based only on estimated performance in the category of health and safety is Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford. The differences among the sites are largely attributable to waste-transportation impacts (radiological and nonradiological) to the public and to nonradiological repository-worker fatalities due to accidents. Note from Table X that each statistical public fatality (row 3) is assigned a value tradeoff four times as high as each statistical worker fatality (row 2). These value tradeoffs also contribute to the differences among the sites shown in row 4. Since the value tradeoffs for statistical worker fatalities indicate that one worker fatality is equivalently as undesirable as an additional $1 million cost, the numbers in rows 1–4 can be interpreted as equivalent statistical worker fatalities associated with the respective sites.

Row 5 shows that the ranking of sites in terms of the environment and socioeconomics performance

Table XII. Base-Case Monetary Equivalent Costs for Various Aggregations of Performance Measures[a]

Row	Performance measure category[b]	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mountain
1	Radiological fatalities (X_1, X_2, X_5, X_7)	17	16	15	30	22
2	Worker fatalities (X_1, X_3, X_5, X_7)	32	33	31	56	25
3	Public fatalities (X_2, X_4, X_6, X_8)	48	40	34	64	58
4	Health and safety($X_1 - X_8$)	80	74	64	120	83
5	Environment and socioeconomics ($X_9 - X_{12}$)	220	119	139	23	71
6	Public near site ($X_2, X_4, X_9 - X_{12}$)	220	121	142	26	71
7	Site impacts ($X_1 - X_4, X_9 - X_{12}$)	249	152	171	78	93
8	Noncosts ($X_1 - X_{12}$)	300	193	203	142	154
9	Noncosts and transportation costs ($X_1 - X_{12}, X_{14}$)	1540	1313	1173	1592	1554
10	Noncosts and repository costs ($X_1 - X_{13}$)	10,700	9693	9203	13,042	7654
11	Total equivalent impact ($X_1 - X_{14}$)	11,940	10,813	10,173	14,492	9054
12	Preclosure utility (0–100 scale)	61.3	66.9	70.1	48.5	75.7

[a] The numbers in rows 1 through 11 in this table represent monetary equivalent costs in millions of dollars rounded to the nearest unit.
[b] See Table I for definitions of the performance measures X_1 through X_{14}.

measures is: Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon. Perhaps most significant here, is the relatively good performance of the Hanford site and the relatively poor performance of the Davis Canyon site.

Row 6 reflects the adverse impacts to people living near the site. It adds the monetary equivalent of the health and safety impacts on the public near a site to the monetary equivalent impacts shown in row 5. The ranking of sites indicated is: Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon. Comparing row 6 with row 5, it is clear that performance in the category of environment and socioeconomics dominates this ranking.

Row 7 adds the health and safety impacts on the workers at the repository and, hence, might be considered to reflect the total impact felt by all members of the community near a site. The ranking of sites matches that given above for rows 5 and 6.

Row 8 in Table XII, labeled "noncosts", aggregates all performance measures except costs. The ranking remains Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon, respectively. This indicates that, given the base-case impacts and value tradeoffs, the environmental and socioeconomic impacts collectively influence the ranking of sites more than the health and safety impacts.

The ranking in the category of noncosts is changed dramatically by the addition of costs. The equivalent-cost impacts in rows 9 and 10 show this. Row 9 shows that when transportation costs are added the ranking becomes: Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford. This ranking matches the ranking of sites that would be obtained if only transportation costs were considered. Row 10 shows the dominant effect of adding repository costs. The ranking becomes: Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford. Thus, the very large differences among the sites in repository costs (i.e., billions of dollars) overwhelm the relatively small differences among the sites shown in rows 8 and 9 (e.g., in row 9, the difference between the sites ranked first and fifth is the equivalent of $419 million, a difference that is overwhelmed by differences of billions of dollars in estimated repository costs).

The dominating influence of costs (especially repository costs) is reflected in the overall equivalent-consequence impacts shown in row 11 of Table XII. The ranking exactly matches the ranking of sites that would be obtained if only repository costs were considered—namely, Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford.

Row 12, the final row of the table, gives the preclosure utility of each site as calculated using Eq. (2). The preclosure utilities are simply a rescaling of the monetary equivalent costs in row 11. The rescaling places the numbers on a 0–100 scale, with 0 representing a poor site whose impacts in every category are the high impacts specified in Table VII, and 100 representing a very good site whose impacts in every category are the low impacts specified in Table VII.

The stability of the overall base-case results was examined by various sensitivity analyses. For all cases, the preclosure ranking was found to be Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford, respectively. This ranking resulted for all reasonable combinations of impacts within the estimated ranges of impacts, for all value judgments thought by DOE managers to be reasonable, and for a variety of attitudes toward risk.

6.2. Postclosure Results

The estimated postclosure releases from a repository at a site (Table IX) and the corresponding postclosure utility calculated using Eq. (3) depend on the postclosure scenario assumed. To obtain a single-number measure for each site's estimated postclosure performance, expected values are appropriate. The expected value of releases (or postclosure utilities) is calculated by weighting the releases (or utilities) obtained under each applicable scenario by the probability of the scenario and summing the results.

The expected postclosure releases and utilities are shown in Table XIII. All of the sites have very low expected releases and very high expected postclosure utilities. The Davis Canyon and Richton Dome sites have the highest expected utilities of 99.99 and are ranked first. The Deaf Smith and Yucca Mountain sites are only slightly lower at 99.98, and the Hanford site is the lowest with an expected postclosure utility of 99.76.

Sensitivity analyses were performed to explore how the overall expected postclosure utilities change with alternative assumptions regarding: (a) the estimated releases resulting under various scenarios, (b)

Table XIII. Computed Base-Case Expected Releases and Postclosure Utilities[a]

Site	Expected releases[b] 0–10,000 years	10,000–100,000 years	0–100,000 years	Expected postclosure utility
Davis Canyon	1.03×10^{-4}	1.03×10^{-3}	1.13×10^{-3}	99.99
Deaf Smith	1.15×10^{-4}	3.26×10^{-3}	3.38×10^{-3}	99.98
Richton Dome	1.04×10^{-4}	1.04×10^{-3}	1.15×10^{-3}	99.99
Hanford	1.25×10^{-3}	3.32×10^{-2}	3.44×10^{-2}	99.76
Yucca Mountain	1.17×10^{-4}	3.29×10^{-3}	3.40×10^{-3}	99.98

[a] See text for explanation.
[b] Fraction of EPA limits for the first 10,000 years after repository closure.

the estimated probabilities of each scenario, (c) the time interval during which scenarios are assumed to occur, and (d) scaling factors, the form of the component utility functions, and risk attitudes. The sensitivity analyses suggest that the most important assumptions in the calculation of expected postclosure utilities are the scenario release estimates and scenario probabilities. Accordingly, an analysis was conducted to estimate an approximate 98% confidence range for the postclosure utilities that might occur at each site, taking into account uncertainty in scores and scenario probabilities. The results are shown in Fig. 3. To provide an intuitive interpretation for the utility numbers shown on the left-hand side of the

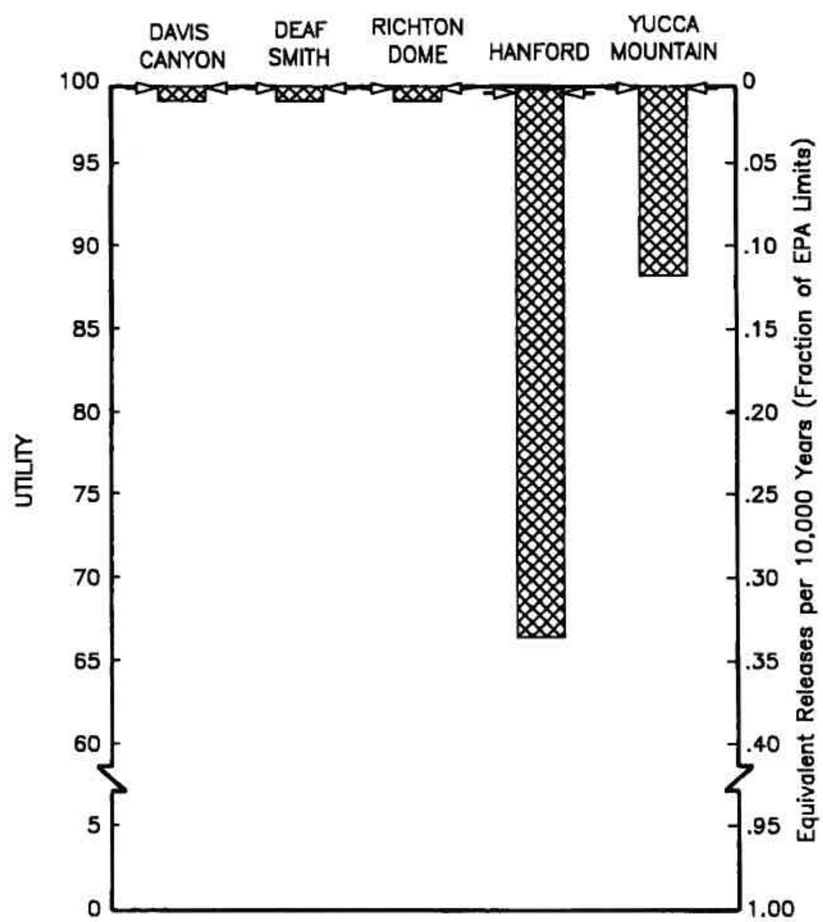

Fig. 3. Ranges illustrating uncertainty in postclosure utilities and releases. Arrowheads indicate the base-case expected utilities.

scale, the right-hand side is calibrated in equivalent releases. Equivalent releases are defined to be the uniform releases per 10,000-year interval that would be assigned a utility equal to the computed utility of the site, whose releases may increase or decrease over time depending on the postclosure scenario. The shapes of the distribution functions that describe the relative probabilities of various postclosure utilities are markedly skewed toward the high end of the ranges. Thus, although the uncertainty in the postclosure performance of the sites is such that any of the utilities within the ranges are possible, utilities near 100 are believed to be much more likely.

The results of the postclosure analysis indicate that:

- Based on judgments of the DOE expert team, all of the sites are expected to provide an exceptionally high degree of waste isolation for at least 100,000 years after repository closure.
- The Davis Canyon, Deaf Smith, Richton Dome, and Yucca Mountain sites appear to be virtually indistinguishable in terms of expected postclosure performance. The Hanford site is an order of magnitude less favorable than the other four sites, but its estimated performance is still far above the threshold of acceptability established by the EPA.
- The confidence in the performance of the three salt sites (Davis Canyon, Deaf Smith, and Richton Dome) is extremely high, and it is higher than that for the nonsalt sites (Hanford and Yucca Mountain).
- The sensitivity analyses indicate that the base-case ranking of Davis Canyon, Richton Dome, Deaf Smith, Yucca Mountain, and Hanford is relatively insensitive to uncertainties or value judgments.

6.3. Composite Analysis

If the preclosure and postclosure results are weighted and combined according to Eq. (1), with postclosure utilities for various scenarios weighted by the probabilities of the scenarios, the resulting composite utility numbers quantify each site's overall desirability. Figure 4 shows how the results depend on the scaling factors k_{pre} and k_{post} assigned to weight preclosure and postclosure performance. As indicated, for essentially all weightings, the ranking is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford, respectively. When nearly all weight is assigned to postclosure (k_{pre} near zero), the ranking is identical to that obtained from the postclosure analysis—that is, the sites are nearly equal, with Hanford just discernibly lower than the others.

The sensitivity of this ranking was investigated through:

- The use of optimistic assumptions for both the postclosure and the preclosure analyses —that is, low release estimates and low probabilities for the scenarios used in the postclosure analysis, and low impact levels for the preclosure analysis.
- The use of pessimistic assumptions for both the postclosure and the preclosure analyses —that is, high release estimates and high probabilities for the scenarios used in the postclosure analysis, and high impact levels for the preclosure analysis.
- Mixed cases in which optimistic or pessimistic assumptions were adopted for the postclosure analysis and the reverse assumption was adopted for the preclosure analysis.

These alternative assumptions produce changes in the site ranking which depend on the weights assigned to preclosure and postclosure. Despite these changes, certain patterns are stable over a wide range of assumptions. For example, the Hanford site is in all cases ranked fifth (i.e., it has the lowest composite utility), regardless of the relative weight assigned to the preclosure and postclosure utilities. This is so because it is ranked fifth for all sets of assumptions in both the preclosure and postclosure analyses. The relative ranking among the salt sites (Richton Dome, Deaf Smith, Davis Canyon) remains the same regardless of whether base-case, optimistic, or pessimistic assumptions are used, unless a very high weight is assigned to the postclosure utility, in which case the composite utilities of the salt sites are essentially equal. Yucca Mountain is the site whose ranking is most affected by the choice of pessimistic, base-case, or optimistic assumptions. Under pessimistic assumptions for postclosure performance, Yucca Mountain receives a lower expected postclosure utility because of the possibility of relatively large radionuclide releases in a scenario involving unexpected features. If pessimistic assumptions are used for postclosure performance, then Yucca Mountain is ranked in the three top-ranked sites only if $k_{post} < \sim 0.35$. Under base-case or optimistic assumptions for post-

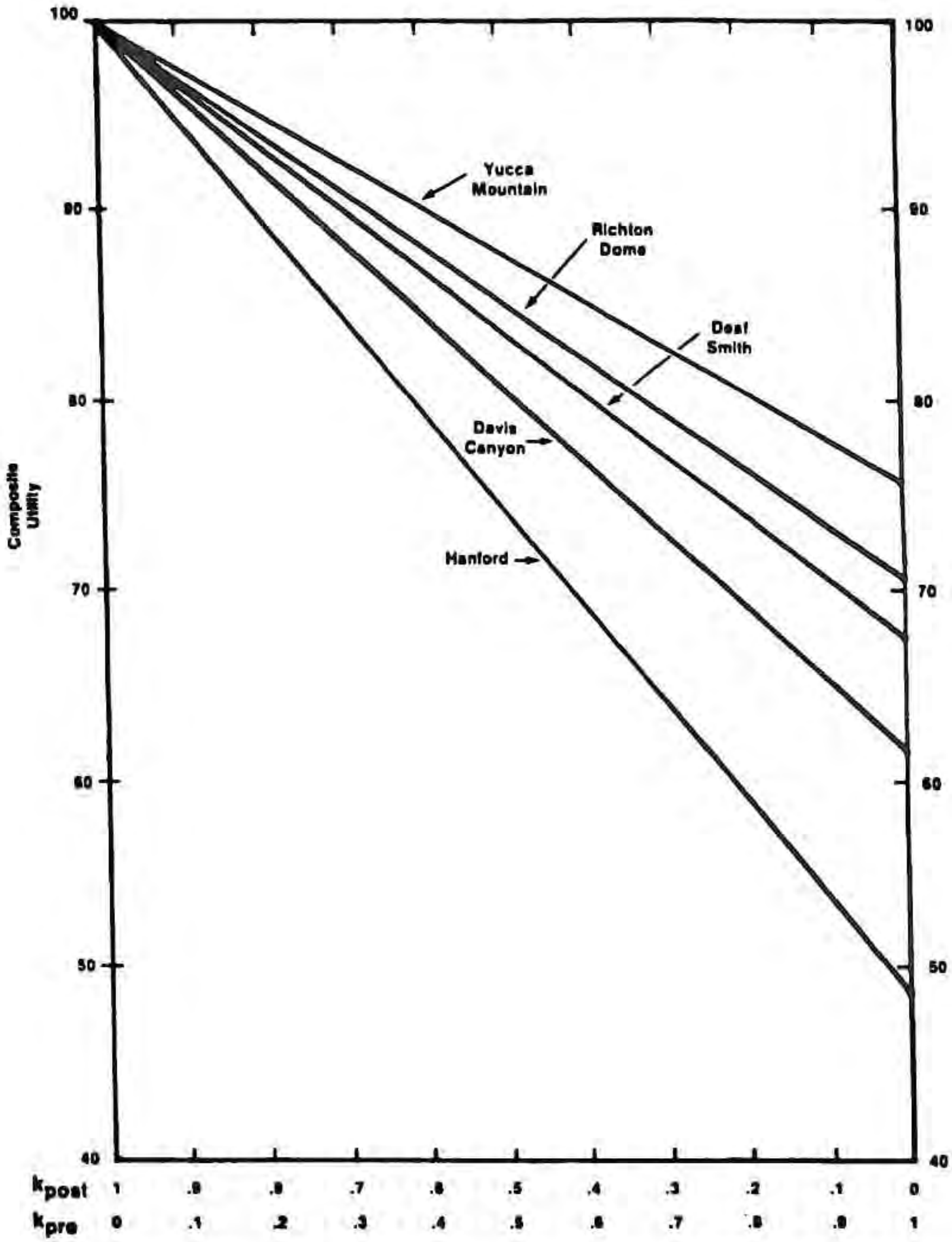

Fig. 4. Composite utilities of sites for all possible preclosure–postclosure weightings and for base-case assumptions.

closure performance, Yucca Mountain is ranked first across nearly the entire ranges of k_{pre} and k_{post}.

To help judge what values of k_{pre} and k_{post} are reasonable, it is helpful to consider the significance of a one-utile change in preclosure and postclosure utilities. In preclosure, the specified value tradeoffs indicate that a one-utile decrease in preclosure utility would be produced, for example, by 50 additional radiological deaths to the public attributable to the facility. In postclosure, the value tradeoffs indicate that a one-utile decrease in postclosure utility would be produced by additional releases in the first 10,000 years equal to 0.019 of the EPA standard. According to an EPA calculation[8], releases at the level of the standard from a repository are estimated to produce 700 additional cancer fatalities in 10,000 years. Assuming linearity, releases equal to 0.019 of the standard would result in $700 \times 0.019 = 13.3$ deaths. Thus, if EPA assumptions are adopted, and if it is assumed that preclosure and postclosure deaths should be counted equally, a preclosure utile has $50/13.3 = 3.76$ the significance of a postclosure utile and should be given 3.76 times the weight (i.e., $k_{pre} = 0.79$, $k_{post} = 0.21$). Table XIV shows the value tradeoffs between preclosure and postclosure cancer fatalities implied by other values for k_{pre} and k_{post}, assuming the EPA relationship between postclosure releases and postclosure fatalities. Because a variety of assumptions and value judgments are possible, DOE elected not to specify precise values for k_{pre} and k_{post}, although values of $k_{pre} = 0.79$ and $k_{post} = 0.21$ provide a useful benchmark.

Table XIV. Value Tradeoffs between Preclosure and Postclosure Radiological Health Effects Implied by Various Values of the Scaling Factors k_{pre} and k_{post} [a]

k_{pre}	k_{post}	Implied value tradeoff between preclosure and postclosure cancer fatalities[b]
1.0	0.0	—
0.99	0.01	1 : 26
0.9	0.1	1 : 2.4
0.8	0.2	1 : 1.1
0.79	0.21	1 : 1
0.7	0.3	1.6 : 1
0.6	0.4	2.5 : 1
0.5	0.5	3.8 : 1
0.4	0.6	5.6 : 1
0.3	0.7	8.8 : 1
0.26	0.74	10 : 1
0.2	0.8	15 : 1
0.1	0.9	34 : 1
0.01	0.99	372 : 1
0.0	1.0	—

[a] Since the scaling factors sum to 1, $k_{post} = 1 - k_{pre}$.

[b] Calculations leading to the results in this column assume the EPA relationship between postclosure radionuclide releases and postclosure facilities.

6.4. Summary of Basic Conclusions from the Analysis

The key conclusions from the analysis can be summarized as follows. The overall ranking under a wide range of assumptions is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford, respectively. This overall ranking is a logical consequence of scientific judgments provided by DOE technical specialists and value judgments provided by OCRWM management. The major difference among the sites contributing to the overall ranking is the estimated difference in preclosure impacts, which in turn is dominated by the difference in total costs. This means that, based on OCRWM value judgments, the estimated differences among the sites in terms of health and safety, environment, and socioeconomic impacts are not significant relative to differences in total costs, which consist of differences in the costs of waste transportation and repository development, construction, operation, and decommissioning.

7. NATIONAL ACADEMY OF SCIENCES REVIEW

On March 24–26, 1986, the Board on Radioactive Waste Management of the National Academy of Sciences reviewed the methods used in the study presented here. Because the Board did not wish to address the ultimate ranking or recommendation of specific sites, its' review was limited to the postclosure analysis for all 5 sites and the preclosure analysis for 1 site. The Board was not provided with the composite analysis results and did not review in detail the data and judgments on which the conclusions of the analysis are based. In its summary, the Board 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... .

> While recognizing that there is no single, generally accepted procedure for integrating technical, economic, environmental, socioeconomic, and health and safety issues for ranking sites, the Board believes that the multiattribute utility method used by DOE is a satisfactory and appropriate decision-aiding tool. 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. These include the diversity of rock types required by the Nuclear Waste Policy Act of 1982, judgments about the ability to license successfully a site including considerations of waste package performance, and judgments about the best set of sites to choose to assure the highest likelihood of a licensable site emerging from the characterization process.[17]

8. THE DEPARTMENT OF ENERGY DECISION AND ANALYSTS' OBSERVATIONS

On May 28, 1986, DOE announced it was recommending 3 sites for characterization: Yucca Mountain, Deaf Smith, and Hanford[4]. The disparity between the results of the analysis and the chosen sites makes it obvious that factors differing from or in addition to those in the analysis were relevant to the decision. Several observations may be helpful in assessing the possible shortcomings of the analysis. As these observations were not part of the formal analysis, they reflect only the views of the authors and are not necessarily shared by other participants in the application.

The rankings produced by the formal analysis are based on a model of the information and preferences relevant to the recommendation decision. Like all models, this one makes certain approximations and does not account for all considerations. In general, a model's results might be legitimately rejected by decision makers because they feel the decision logic is inappropriate, they disagree with the model's inputs, or they feel that key objectives have been omitted. Comments on each of these possibilities are provided.

The logic of the analysis involved individually evaluating 5 potential repository sites. Yet the DOE recommendation decision is analogous to selecting a portfolio consisting of the best 3 of 5 sites. It does not necessarily follow that the best 3 sites in the evaluation of single sites should comprise the best collection of 3 sites. This is because certain attributes desired of the group, such as including diversity of geohydrologic settings and rock types (to protect against the possibility that characterization will uncover a serious problem common to all sites in a particular geologic setting or rock type) cannot be associated with individual sites. The evaluation of individual sites is directly relevant to the portfolio evaluation problem, but other factors also need to be considered. This limitation was recognized from the beginning of the analysis.

Disagreements regarding the appropriate base-case inputs to a model are always possible. For example, the measure of total costs associated with the selection of each site can be altered greatly by adopting different assumptions regarding the need for and timing of activities (such as whether backfilling of caverns occurs during or after the completion of waste emplacement), and by selecting different cost escalation and discount rates. Another possibility for differences in input assumptions concerns value judgments. Although the value tradeoffs used as inputs for the MUA analysis were provided by senior managers of OCRWM, the recommendation decision is the responsibility of the Secretary of Energy. The value judgments assessed were meant to reflect those governing the decision, but they may not do that well. For example, in announcing the Secretary's decision, DOE noted that a sensitivity analysis showed that when repository and transportation costs are ignored, the formal analysis, considering preclosure impacts only, indicated that Deaf Smith is ranked over Richton Dome for preclosure considerations and that "Hanford becomes the most desirable site, a telling factor"[4].

Several objectives that might have been included in the analysis were excluded to avoid complexity that might obscure potential insights and possible inconsistencies with the siting guidelines. These included considerations of the degree of local opposition to the repository, less-than-fatal health effects, fear and anxiety due to waste transportation, equity considerations, and licensability. To examine the significance of these omissions, one needs to appraise the degree to which they are appropriate and distinguish the sites, and compare this to the degree to which the sites are distinguished by the analysis.

Despite the differences in the base-case analysis and DOE's decision, the Department has stated that the "methodology provided significant insights on both the relative desirability of the sites and identification of the factors that most influence the desirability," and concludes that it was of assistance to the decision-making process[4]. Although all relevant factors are not accounted for in the analysis, DOE should be commended for its efforts to quantify and make explicit many of the factors and considerations specified as relevant by their siting guidelines. By conducting this analysis and justifying their decision in terms of the insights derived from it, DOE has clearly articulated many technical judgments regarding the performance and impacts of a repository at each of the nominated sites, as well as many of the value judgments that specify how objectives should be traded-off against one another. Most complicated policy decisions are not subjected to such an explicit analysis, so the key judgments underlying decisions typically remain implicit and unreviewable by interested parties.

Once an analysis is complete and its insights drawn, directions for further analysis building on existing results often appear. For this case, potentially important extensions include: (a) a portfolio analysis to explicitly account for the value of diversity and the interdependences among the uncertainties in estimated site impacts[18]; (b) using technical panels of independent experts to broaden the basis for scientific inputs; and (c) inviting the states, local communities, and other interested parties to participate in the identification of objectives and specification of value judgments to ensure that their viewpoints are understood and properly accounted for in the decision-making process. Whether these and other extensions would be worth the effort depends on whether the additional resources required can be justified in terms of the value of insights anticipated from the analysis and the contributions of these extensions to the decision process. The fact that many people are concerned with the risks and inequities associated with nuclear waste disposal suggests that the ability to clearly explain the technical basis for controversial decisions has high value.

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